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Enhanced ultraviolet-B radiation reduces methane emission in one of the oldest and largest rice terraces in China but triggers new challenges

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Ultraviolet-B (UV-B) radiation enhancement and climate warming are two critical environmental issues worldwide. Understanding the effects of enhanced UV-B radiation on methane (CH_4) emission and rice growth in paddy fields are fundamental for human sustainability. *In situ* field experiments with ambient and supplemental UV-B radiation stresses were conducted in paddy fields subjected to prolonged flooding at Yuanyang Terraces, Southwest China. Annual dynamics and driving factors of CH_4 emission were investigated; the effects of enhanced UV-B radiation on soil carbon conversion, enzyme activities and rice growth were studied. Yuanyang Terrace's CH_4 emission levels were 1.6 and 3.3 times higher than China's and global mean values, respectively. Weather conditions (27.02%) and the stage of rice cultivation (25.65%) were the predominant factors in driving CH_4 emission. During the winter fallow period, enhanced UV-B principally affected rice straw and its decomposition, subsequently changing both soil enzyme activities and labile organic carbon levels to reduce CH_4 emission. On the other hand, during the rice-growing period, enhanced UV-B affected rice growth, subsequently changing rhizospheric microorganism and soil enzyme activities to reduce CH_4 emission. Meanwhile, enhanced UV-B could affect the growing of rice to further change the balance between CH_4 and CO_2 in the rhizosphere, and the corresponding trade-off could reduce the shifts in global warming potential of rice terraces. In total, enhanced UV-B reduced CH_4 emission in the rice terraces by 15.70%, but would increase CO_2 and N_2O emissions, and negatively affect paddy yields, thus hindering regional food security and sustainable development. Therefore, integrating a consideration of the mitigation of greenhouse gas emissions with a concern for food security is a prospect for future research.

KEYWORDS

carbon dioxide emission, nitrous oxide emission, soil enzyme activity, labile organic carbon, rice yield, trade-off

1 Introduction

Methane (CH_4) is a key greenhouse gas, only second to carbon dioxide (CO_2); its warming potential is 25 times of that of CO_2, and its contribution rate to the global greenhouse effect is approximately 20% (Kirschke et al., 2013). Atmospheric CH_4 mixing ratio has increased by 6.8 ppb per year over the last decade (SAWA et al., 2021). Rice paddies are the dominant anthropogenic source of CH_4, and the latter's annual emission from this source is approximately 31–112 Tg or approximately 9–19% of the total global CH_4 emissions (Forster et al., 2007; Rahman and Yamamoto 2020a; Rosentreter et al., 2021). Yet few studies regarding the monthly dynamics of CH_4 emission and its responses to enhanced Ultraviolet-B (UV-B, 280–315 nm) radiation have been conducted in rice terraces.

Our first aim is to understand the CH_4 emission pattern and its driving factors in the rice paddies of Yuanyang Terraces. Rice terrace farming is the major source of livelihoods for a large section of hillside farmers worldwide (Chapagain and Raizada 2017). The Yuanyang Terraces is one of the oldest and largest rice terraces in China, and considered to be an exemplary representative of this traditional agro-system. Influenced by local climate and customs, this type of terrace is flooded all year round without a rice field sunning process. Notably, prolonged flooding could lead to high flux in CH_4 emissions (Wang et al., 2021). Furthermore, UV-B radiation enhancement *via* ozone attenuation is another major issue in global climate change (Johnson et al., 2002), and since the Yuanyang Terraces are located on the Yunnan-Guizhou Plateau, it is more susceptible to this enhancement. Therefore, understanding the characteristics of emission during different periods (winter fallow, rice-growing) in this terrace agriculture is essential to regional food safety and carbon (C) management.

Our second aim is to understand the effects of enhanced UV-B radiation on CH_4 emission patterns and the driving factors for these effects. During the rice-growing period, studies have found enhanced UV-B to affect ratios in photochemical reactions and reactive oxygen species, and subsequently increase CH_4 emissions (McLeod et al., 2008; Zepp et al., 2011; Lou et al., 2016). However, some studies have obtained opposing results, showing that enhanced UV-B can indirectly affect CH_4 emission in paddy fields, through producing more recalcitrant substrates (i.e., lignin), hindering aerenchymas formation, *etc.*, thereby further decreasing the straw decomposition rate and CH_4 emission levels (Li et al., 2018; Zhou et al., 2018). Our previous study also found that enhanced UV-B could affect rice root exudation and corresponding composition of rhizospheric microbes, which further decrease CH_4 emissions (He et al., 2016). Furthermore, during the winter fallow period, studies have indicated that exogenous organic C input (straw, *etc.*) and corresponding labile organic C variations became the predominant factors in driving CH_4 emission, while UV-B radiation can also increase the presence of OH radicals, leading to CH_4 destruction and the consequent reduction in its emission (Fenimore 1969). In general, these inconsistencies in research findings are often due to the influence from the development stage of paddy: the processes in question are microenvironmental and dependent on the stage of rice development (McLeod et al., 2008; Fernández-Baca et al., 2021). Therefore, we hypothesize that the effects of enhanced UV-B radiation on CH_4 emission patterns would be different between the winter fallow and different rice-growing periods.

Our third aim is to study whether there is a trade-off between CH_4 and other greenhouse gas emissions in rice terraces under UV-B radiation enhancement. Recent global studies have demonstrated a balance between CH_4 and carbon dioxide (CO_2) emissions in peatlands (Zhu et al., 2019; Huang et al., 2021). Furthermore, Hu found that enhanced UV-B reduced CH_4 but meanwhile increased nitrous oxide (N_2O) emissions in paddy fields (Hu et al., 2011); Ma also found a trade-off between CH_4 and N_2O emissions in paddy fields, whereby the former increased as the latter decreased (Ma et al., 2009). This balance can be explained as the conservation of matter and corresponding C and nitrogen transformation, which link closely to shifts in soil oxidation-deoxidation environments and subsequent variations in microbial composition (Chen et al., 2016). In the Yuanyang Rice Terraces, our previous studies indicated that enhanced UV-B could affect rhizospheric pH and the oxidation-deoxidation environment in the rhizosphere by changing the composition and quantity of root exudates, which would subsequently affect CH_4 emission (Xu et al., 2015; Chen et al., 2016; He et al., 2016). Therefore, we hypothesize that enhanced UV-B could affect rice-growing to further alter the balance between CH_4, CO_2, and N_2O emissions in rice terraces.

In this study, *in situ* field experiments with ambient and supplemental UV-B radiation stresses were conducted in a year-round flooded paddy field at Yuanyang Terraces. The annual dynamics of labile organic C, C transformation enzyme activities, and greenhouse gases *etc.*, were studied to understand the pattern of CH_4 emission and its responses to enhanced UV-B radiation. Meanwhile, partial least squares path analysis, canonical correspondence analysis, and linear mixed model were employed to analyze the driving factors of CH_4 emission and the trade-off between this and other greenhouse gas emissions. This study contributes to an understanding of the processes and mechanisms of UV-B radiation influencing CH_4 emissions in rice fields; and these influences should be considered when establishing biogeochemical models in response to global changes.

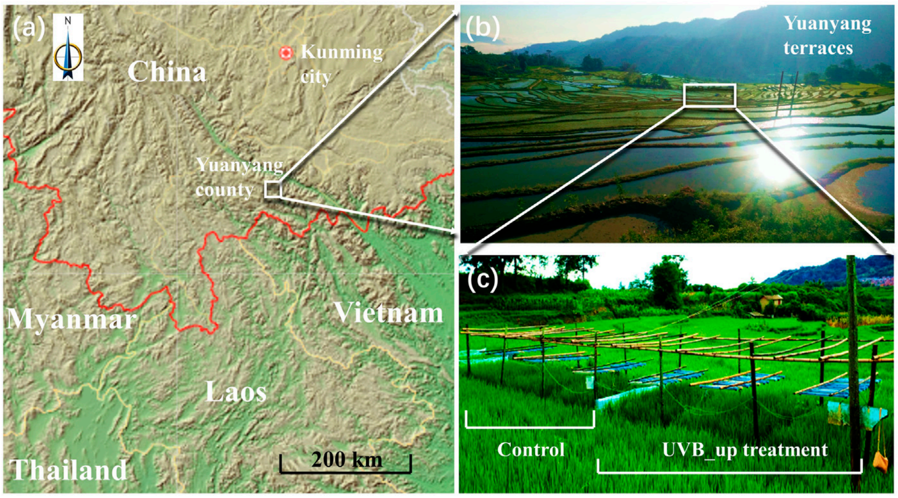

FIGURE 1
Topographical map and the location of Yuanyang County **(A)**; photos of Yuanyang Terraces **(B)** and *in situ* field experiments **(C)**. Control: treatment under natural conditions; UVB_up: treatment under enhanced UV-B radiation.

TABLE 1 Monthly dynamics of meteorological conditions in Yuanyang Terraces.

	January	February	March	April	May	June	July	August	September	October	November	December
Per_nat_uvb	16.08	20.97	17.78	9.61	4.95	1.34	0.98	1.06	2.43	4.40	7.58	12.81
Mean_prec	39.10	41.02	44.18	83.94	194.41	227.97	218.72	188.38	144.39	110.94	89.91	40.34
Mean_evap	92.32	119.32	191.70	207.56	193.15	134.17	123.75	126.07	110.07	91.69	76.49	82.80
Mean_temp	14.40	17.40	23.40	28.40	32.40	32.60	30.80	29.40	28.80	26.40	20.80	15.40

Per_nat_uvb: monthly percentage of natural solar radiation (%); Mean_prec: mean monthly rainfall (mm); Mean_evap: mean monthly evaporation (mm); Mean_temp: average monthly temperature (°C).

2 Materials and methods

2.1 Study site and experimental design

The Yuanyang Terraces are located in Xinjie town, Yuanyang county, Yunnan province, Southwest China (23°73′N; 102°44′E) (Figure 1). The Yuanyang Terraces have a mountain monsoon climate with distinct dry and wet seasons. The annual sunshine duration is 1770.2 h, accounting for 40% of the astronomically possible sunshine hours. The annual average temperature, annual average precipitation, altitude are 25°C (Table 1), 1,397.6 mm and 1,600 m, respectively. As one of the oldest and largest rice terraces in China, the Yuanyang Terraces are considered to be an exemplary representatives of this traditional agro-system (Filloux et al., 2018).

Six monitoring plots (2.25 m × 3.9 m) were established at Yuanyang Terraces. At summer solstice, the background value of UV-B radiation is 10 kJ.m^{-2}.d^{-1}. Three of the six monitoring plots were treated with enhanced UV-B radiation (5.0 kJ.m^{-2}.d^{-1}), which was equivalent to 20% of atmospheric ozone attenuation in the surrounding area (Li et al., 2020). The other three monitoring plots were left under natural light as controls. The whole experiment lasted 1 year, and can be divided into two stages. October 2016 to April 2017 was the winter fallow period. Following traditional farming practices, the winter fallow period had flooding conditions of water at a depth of 10–15 cm, and rice straws were returned to each plot (8.8 kg). The rice-growing period is from May to September (2017 in the present study). Rice was planted in 14 rows × 16 columns, and 6-row and 4-column rice was set around each plot as the guarding row. Flooding conditions remained consistent throughout the entire winter fallow period. No pesticides or chemical fertilizers were used and flooded during the rice-growing period (water at 10–15 cm depth). For other information please see Section 1 in the Supporting Information (SI) and our previous studies (Lou, Zhou, and Ren 2012; Yong-Mei et al., 2016; Wang et al., 2018).

2.2 Sampling and data collection

Meteorological information, such as precipitation, evaporation, temperature, and natural solar radiation were collected from the local weather station. In terms of soil samples, the mixed surface soil (0–20 cm) in the rice field was collected by a soil sampler on the 15th day of each month. One kg of soil was collected in each plot. The fresh soils were placed into a low-temperature storage box, rapidly transported to the laboratory, and then passed through a nylon mesh sieve to remove gravel impurities. C transformation enzyme activities, such as those involving polyphenol oxidase, β-Glucosidase, invertase and Cellulase were tested using the pyrogallic acid colorimetric method, p-nitrophenol colorimetric method, 3,5-dinitrosalicylic acid colorimetric method and anthrone colorimetric method, respectively (Frankeberger and Johanson 1983; Eivazi and Tabatabai 1988; Deng and Tabatabai 1994; Bach et al., 2013). Meanwhile, labile organic C contents, such as dissolved organic C, microbial biomass C and easily oxidized C were tested by the K_2SO_4 extraction method, chloroform fumigation extraction method and potassium permanganate oxidation method, respectively (Blair, Lefroy, and Lisle 1995; Jones et al., 2006; Wu et al., 2006).

2.3 Greenhouse gas collection and measurement

The static chamber method was employed to collect greenhouse gas samples from the rice field (Zepp et al., 2011; He et al., 2014). The static chamber was made using a light-proof polyvinyl chloride material and had a cylinder with radius 30 cm and height adjustable according to rice growth. The sampling time was between 9:00 and 11:00 a.m. on the 15th day of each month. According to Nayak's method, gas samples (CH_4, CO_2, N_2O) were analyzed using an Agilent 7890B gas chromatograph (Nayak et al., 2006). The warming potential effect of CH_4 and N_2O are respectively 25 and 298 times that of CO_2 over a 100-year horizon. Therefore, we used the global warming potential (GWP) index to convert the warming potential of all kinds of greenhouse gases into CO_2 equivalents (Eq. 1), which benefited further comparison (Shi et al., 2020).

$$GWP = CO_2 + 25 \times CH_4 + 298 \times N_2O \tag{1}$$

2.4 Statistical analysis

First, the generalized additive model was used in R software using the mgcv package (Yan et al., 2021), to study the annual CH_4 emission trend in rice terraces. Canonical analyses and corresponding variation partitioning to further understand the contributions from each predictor aspect to this annual trend (weather condition, cultivation stage, UV-B radiation intensity, *etc.*), were carried out in R software using the rdacca.hp package (Lai et al., 2022). To test the contributions from and pathways of enhanced UV-B radiation in influencing CH_4 emission, we performed partial least squares path analysis at the winter fallow and rice-growing periods in R software using the plspm package (Sanchez 2015). Furthermore, the natural log-transformed response ratios (RRs, effect sizes) of each variable (e.g., CH_4 emission, enzyme activity and labile organic C, *etc.*) at enhanced UV-B radiation treatments (X_{UVB}), compared to those under natural light condition (X_C), were calculated at the end of experiment, and consequently used to calculate the effect of enhanced UV-B radiation treatments (Eq. 2). The variance of RRs (v) was approximated using Eq. 3, where $S_C{}^2$ and $S_{UVB}{}^2$ are the standard deviations in the control and enhanced UV-B treatments, and N_c and N_{UVB} are the sample sizes in the controls and enhanced UV-B treatments, respectively. To quantify the general pattern of each variable's response to enhanced UV-B in the Yuanyang Terraces, cumulative effect sizes were calculated using mixed models in R software using the metafor package (Yan et al., 2018).

$$LnRRs = \ln \frac{X_{UVB}}{X_C} = \ln X_{UVB} - \ln X_C \tag{2}$$

$$v = \frac{S_{UVB}^2}{N_{UVB}\sqrt{X_{UVB}}} + \frac{S_C^2}{N_C\sqrt{X_C}} \tag{3}$$

The enhanced UV-B effects were significant if the 95% confidence intervals of the cumulative effect size did not overlap with zero. The results are reported as RRs and as percentage changes (Per_{change}) by back-transforming RRs to ratios in the original scale (Eq. 4).

$$Per_{change} = (\exp(RRs) - 1) \times 100\% \tag{4}$$

3 Results

3.1 Seasonal dynamics of CH_4 emission and their driving factors in rice terraces

The intensity of CH_4 emissions at Yuanyang Terraces (18.10 $mg/m^2/h$) was 1.6 times and 3.3 times higher than China's and global mean values, respectively (Figure 2A; Section 2 in SI). Weather conditions (27.02%) and the stage of rice cultivation (25.65%) were the predominant factors driving dynamics in soil C transformation enzyme activities and changes in labile organic C contents, subsequently affecting CH_4 emission patterns (Figure 2B). Across the entire year, emission peaks appeared in July and September, which are during the rice-growing period. In total, CH_4 emission flux during the rice-growing period accounted for 64.48% of annual emissions, with emission intensity (28.0 $mg/m^2/h$) being 2.5 times higher than that during the winter fallow period. CH_4 emissions in the winter fallow period reached its peak and minimum values in October (25.81 $mg/m^2/h$) and April

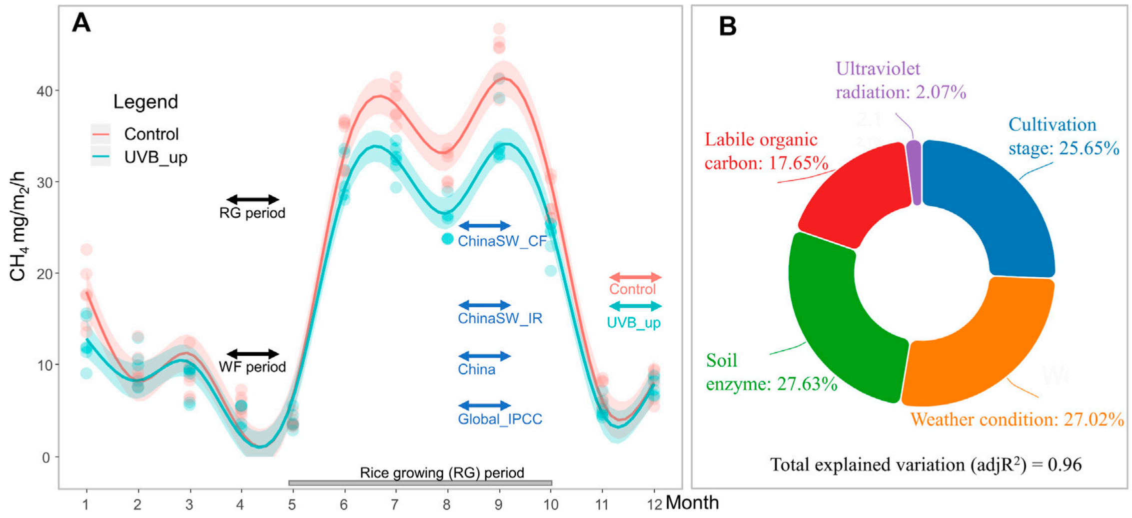

FIGURE 2
(A) Monthly dynamics of CH_4 emission under natural conditions (control, in red) and the influence of enhanced UV-B radiation (UVB_up, in green) at Yuanyang Terraces. Trends in CH_4 emissions were described using a generalized additive model (with 95% confidence intervals given). The double-headed black arrows show mean CH_4 emissions in the winter fallow period (WF period) and the rice-growing period (RG period) in this study. The double-headed blue arrows show mean CH_4 emissions in a continuously flooded paddy field in southwest China (ChinaSW_CF) and in an intermittently irrigated paddy field in southwest China (ChinaSW_IR), the mean value of CH_4 emissions over the whole of China (China) (Yan et al., 2003), and the global CH_4 baseline emission factor (Global_IPCC) (Rahman and Yamamoto 2020b). **(B)** Relative contribution (%) of each explanatory variable to CH_4 emission dynamics is presented. Meanwhile, the adjusted coefficient of determination for the entire model (R^2) is given. Labile organic carbon: easily oxidized carbon, microbial biomass carbon, dissolved organic carbon; Soil enzyme: polyphenol oxidase, β-glucosidase, invertase, cellulase; Weather condition: temperature, precipitation, evaporation; Cultivation stage: winter fallow, different rice-growing stages.

(5.04 mg/m^2/h) respectively. The annual mean emission intensity is relatively low, but remained 2 times higher than the global baseline emission factor given by the IPCC (5.42 mg/m^2/h). With regard to the effects of UV-B radiation, overall, it was less of a factor contributing to shifts in the monthly trends of CH_4 emission (2.07%) (Figure 2B).

3.2 Effects of enhanced UV-B radiation on CH_4 emission from rice terraces

Although enhanced UV-B was a lesser contributor to changing monthly trends in CH_4 emissions, it significantly reduced the intensity of CH_4 emissions from the rice terraces over the whole year by 15.70% (Figure 2A; Section 2 in SI). This reduction had less to do with shifts in weather and natural UV-B conditions, but closely related to the stage of cultivation of rice (Figure 3; Section 3 in SI). In general, CH_4 emission patterns and their driving pathways were different during the rice-growing and winter fallow periods. In the winter fallow period, CH_4 emission was tightly linked with both soil C transformation enzyme activities and labile organic C contents. By affecting both labile organic C contents (path coefficient = 0.19) and enzyme activities (path coefficient = 0.15), enhanced UV-B further reduced CH_4 emissions indirectly. Specifically, enhanced UV-B increased β-glucosidase by 17.40%, decreased easily oxidized C by 18.10%, and subsequently, reduced CH_4 emissions from 11.9 to 10.1 mg/m^2/h in the winter fallow period (Figures 2; Figure 4). In the rice-growing period, shifts in soil enzyme activities were the predominant factor affecting CH_4 emissions, while the contribution from labile organic C was minimal (path coefficient = 0.14 and 0.01, respectively). During rice-growing, enhanced UV-B reduced microbial biomass C by 19.70%, increased cellulase activity by 22.10%, and decreased invertase activity by 14% (Section 4 and Section 5 in SI). Notably, it was determined that enhanced UV-B eventually reduced CH_4 emissions in the rice-growing period by 16.12% (R^2=0.75). Soil enzyme activity was the predominant factor in driving this reduction *via* both direct and indirect effects (Figure 2). However, with the current variables, it was hard to explain exactly how enhanced UV-B could affect the corresponding effect pathway during the rice-growing period (path coefficient =0.15).

3.3 Effects of enhanced UV-B radiation on C sequestration and greenhouse gas emissions in rice terraces

Enhanced UV-B reduced the rice terraces' CH_4 emission both in the winter fallow period (15.13%) and the rice-

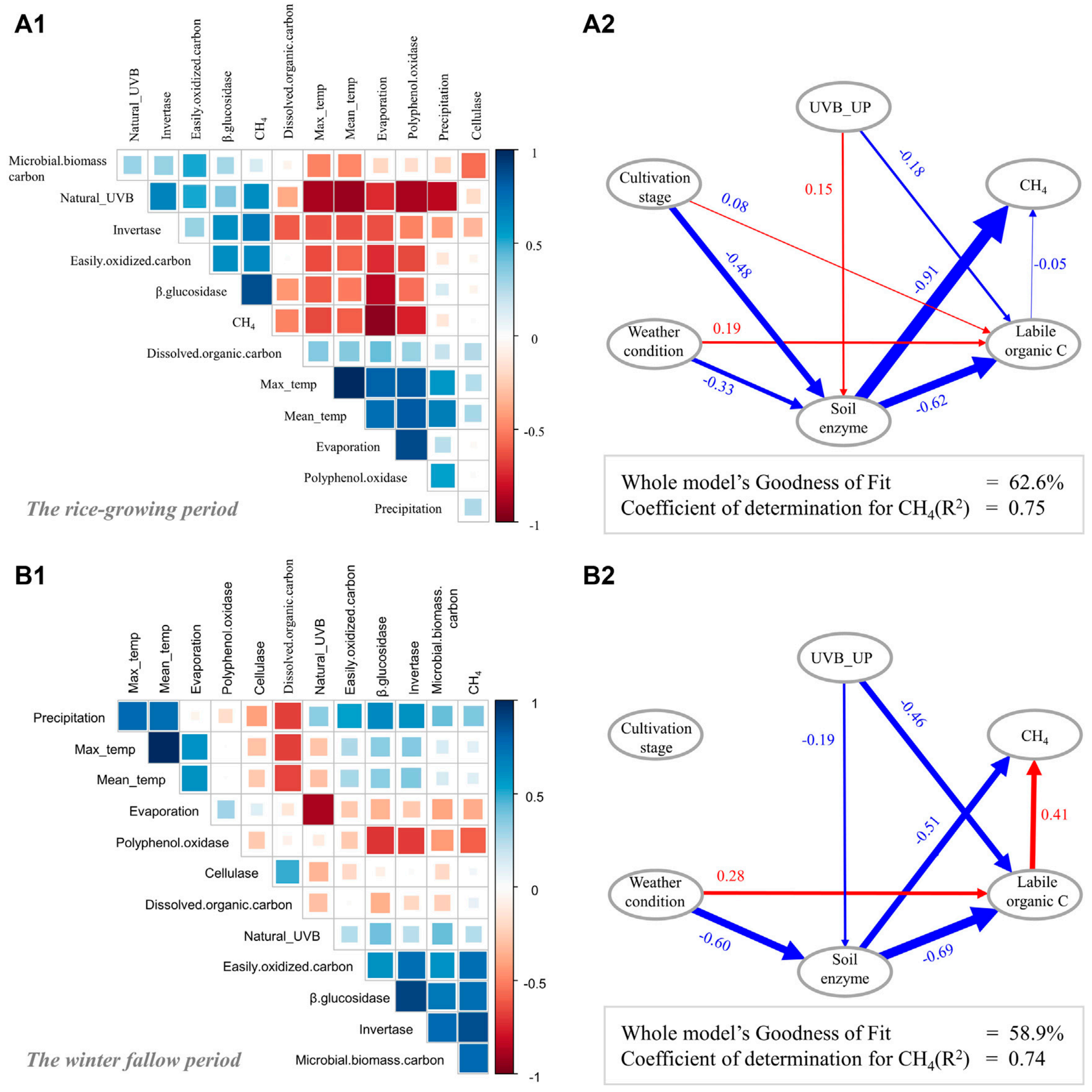

FIGURE 3
Correlation coefficients among C transformation enzyme activities, labile organic carbon contents and CH_4 emissions during the rice-growing period **(A1)** and the winter fallow period **(B1)**. Partial least squares path analysis for CH_4 emissions during the rice-growing period **(A2)** and the winter fallow period **(B2)**, showing the relationships among cultivation stage, weather conditions (including temperature, precipitation, and evaporation), enhanced UV-B, and the corresponding pathway to driving CH_4 emissions. The coefficient of determination (R^2, %) to each microbial feature and the model's goodness of fit (GoF, %) are given.

growing period (16.12%), but inconsistent results were observed for CO_2 and N_2O emissions and corresponding C sequestration. Specifically, in the winter fallow period, enhanced UV-B increased β-glucosidase activity, reduced easily oxidized C contents, and subsequently reduced both CH_4 and N_2O emissions by 14.80% and 18.92%, respectively. In sum enhanced UV-B led to a reduction in GWP by 17.30% during the winter fallow period. In the rice-growing period, enhanced UV-B increased CO_2 emissions by 15.00%, and the mean value of GWP by 6.21%. Furthermore, enhanced UV-B significantly reduced rice biomass, seed size/weight, rice grain yield and rhizospheric microbial biomass by 32.10, 3.10, 9.30, and 19.70%, respectively. Overall, although enhanced UV-B significantly mitigated CH_4 emissions in the rice terrace, it did not reduce the total GWP over the whole year. In contrast, it increased CO_2 emissions, and reduced C sequestration in rice biomass and microbial biomass during the rice-growing period. Furthermore, it also diminished rice grain yield (Figure 4 ; Section 6 in SI).

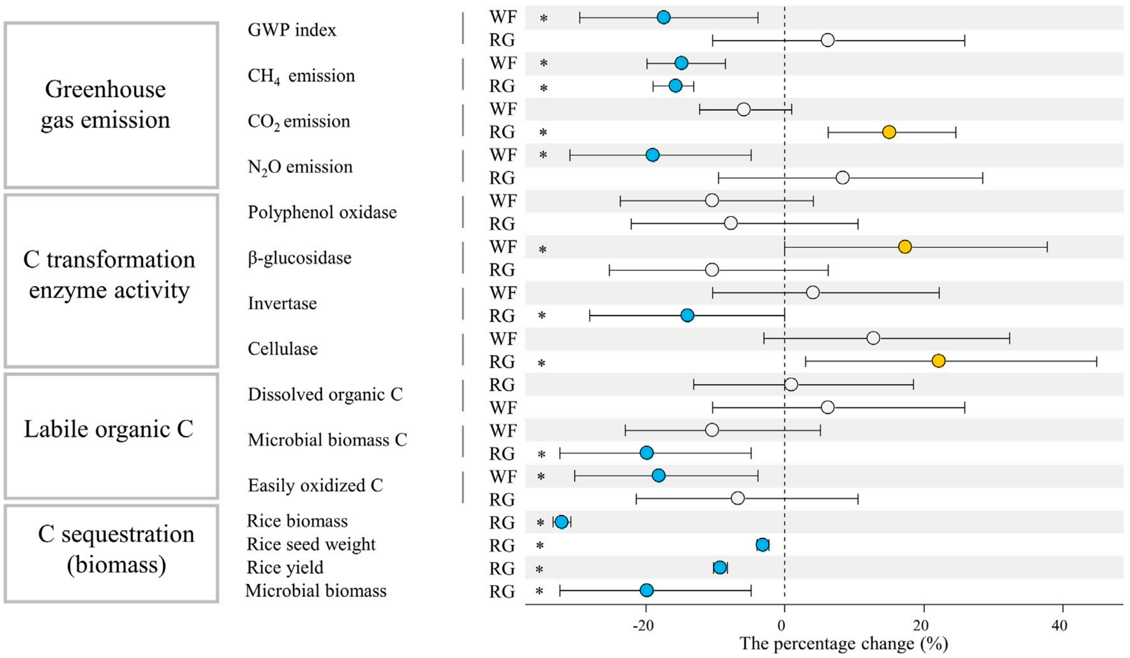

FIGURE 4
All dots represent the percentage change (%) of each variable at 95% confidence intervals (CIs), due to enhanced UV-B treatment when compared to exposure to natural conditions (Eq. 4). Mean values <0 indicate, comparative to the natural condition, reductions in corresponding variables due to enhanced UV-B (blue dots), while mean values >0 reflect significant increments due to enhanced UV-B treatment (yellow dots). When error bars intersect the zero line, these indicate no significant differences between the effects of enhanced UV-B treatment and results occurring under natural conditions (white dots). WF: in the winter fallow period; IR: in the rice-growing period. All significant differences have been marked with asterisks.

4 Discussion

4.1 Mitigation of CH_4 emission remains urgent in this traditional agro-system

The Yuanyang Terraces is one of the oldest and largest rice terraces in China and is known to protect and be in harmony with nature (Fullen et al., 2017). This agro-system is also the major source of livelihoods for local hillside farmers and an important provider of regional food security. It has experienced thousands of years of cultivation; prolonged flooding and rice straw returning methods practiced there have had a long tradition. Intensity of CH_4 emissions at the terraces (18.10 mg/m^2/h) is significantly lower than that of other prolonged flooding paddy fields in southwest China (25.30 mg/m^2/h) (Yan et al., 2003), suggesting that the Yuanyang Terraces is a good rice planting system in this region (Figure 2; Table 2). However, when compared to the mean across China and the world, this emission intensity is still high (1.6 times and 3.3 times higher, respectively), such that CH_4 mitigation remains urgent. Weather conditions (27.02%) and the stage of cultivation of rice (25.65%) were the predominant factors in affecting CH_4 emissions in the Yuanyang Terraces, and a detailed understanding of the driving factors is essential for future mitigation management.

The risk of CH_4 emissions is different across rice planting systems and cultivation stages (Figure 2; Figure 3). In general, emission risks in single rice paddy and late rice paddy are higher than those in early rice paddy fields, the emission risks in continuously flooded paddy fields are higher than those in intermittently irrigated paddy fields, and organic input (through rice straw return, manure return, *etc.*) increases the emission risk (Table 2). In addition, different emission risks are observed in different seasons and at different cultivation stages. In Yuanyang Terraces, the intensity of CH_4 emission in the rice-growing period was significantly (2.5 times) higher than that in the winter fallow period, which is in accordance with previous studies. Differing from Yan's finding that CH_4 emissions reach their sole peak in August on the national scale, we found CH_4 emissions to reach their peaks in July (35.50 mg/m^2/h) and September (39.60 mg/m^2/h) at the Yuanyang Terraces. This difference can be explained by the fact that instead of climatic and soil factors, the developmental stage of rice and its corresponding soil microbial variations predominantly contribute to CH_4 emissions at the local scale. Fernández-Baca's study supports our finding, by showing that CH_4

TABLE 2 Region-Specific CH_4 Emission Factors (mean value, mg/m²/h).

Region	Cropping system	Organic input	CH_4 emission	Irrigation	References
Yuanyang	Single rice	Yes	18.10	CF	This study
Global	All	—	5.40	—	Rahman and Yamamoto (2020b)
China	All	—	10.90	—	Yan et al. (2003)
China	Single rice	—	13.70	—	Wei, Sun, and Huang (2012)
China	Early rice	—	10.80	—	Wei, Sun, and Huang (2012)
China	Late rice	—	18.80	—	Wei, Sun, and Huang (2012)
China	Single rice	—	8.20	—	Wang et al. (2021)
China	Early rice	—	21.00	—	Wang et al. (2021)
China	Late rice	—	10.10	—	Wang et al. (2021)
China N	Single rice	Yes	5.50	IR	Yan et al. (2003)
China N	Single rice	Yes	16.30	CF	Yan et al. (2003)
China N	Single rice	No	2.75	IR	Yan et al. (2003)
China N	Single rice	No	7.80	CF	Yan et al. (2003)
China SW	All	—	16.80	—	Shi et al. (2010)
China SW	Single rice	Yes	15.60	IR	Yan et al. (2003)
China SW	Single rice	Yes	25.30	CF	Yan et al. (2003)
China SW	Single rice	No	7.80	IR	Yan et al. (2003)
China SW	Single rice	No	12.70	CF	Yan et al. (2003)
China SW	Single rice	—	18.40	—	Wei, Sun, and Huang (2012)

Abbreviations: IPCC, The Intergovernmental panel on climate change; IR, Intermittently irrigated paddy; CF, Continuously flooded paddy; Yes, With organic input; No, Without organic input; China N, North China; China SW, Southwest China.

emissions at the booting stage in rice (in August for this present study) are often at a lower level than those of other stages (Fernández-Baca et al., 2021). Therefore, management by stages is required to reduce CH_4 emissions from the Yuanyang rice terraces.

4.2 CH_4 emissions in rice terraces under enhanced ultraviolet-B radiation

Enhanced UV-B can reduce CH_4 emissions in both the winter fallow period and the rice-growing period at similar reduction ratios (15.13% and 16.12%) (Figure 2; Figure 4). However, for such a reduction, there are different driving pathways and reduction quantities over the two periods. In the winter fallow period, enhanced UV-B reduced CH_4 emissions by affecting both soil labile organic C contents and C transformation enzyme activities. Specifically, it reduced emissions by causing significant increases in β-glucosidase activities. Meanwhile, it can affect rice straw composition, for example by increasing lignin and total phenols content to affect rice straw decomposition, and subsequently lead to a decline in easily-oxidized C content in the soil (Figure 4; Section 6 in SI). This phenomenon is consistent with the previous finding that UV-B radiation reduces CH_4 emissions in rice fields (Hu et al., 2011; Wang et al., 2018). This reduction can be explained by the increase in defensive substances in rice straws due to enhanced UV-B, such as flavonoids, polyphenols and lignins, which are resistant to decomposition (Zhou et al., 2018). Other studies have also indicated that enhanced UV-B can additionally lead to an increase in the presence of OH radicals, leading to CH_4 destruction and a consequent reduction in its emission (Fenimore 1969). Nevertheless, enhanced UV-B affects soil labile organic C contents to further reduce CH_4 emissions in the winter fallow period, which is not the case for the rice-growing period.

During the rice-growing period, enhanced UV-B predominantly affected soil C transformation enzyme activities to further reduce CH_4 emissions (path coefficient = 0.14), while the variation in soil labile organic C contents contributed less to CH_4 emission (path coefficient = 0.01). Specifically, enhanced UV-B led to declines in microbial biomass C and invertase activity, while significantly increasing cellulase activity. These phenomena can be explained by (1) UV-B radiation cannot directly permeate the water layer to act upon the rice field soil, but it can change the composition and quantity of rice root exudates, causing quantitative increases in oxalic acid and succinic acid secreted *via* rice roots (He et al., 2014), altering the community composition and quantity of rhizospheric microorganisms (He et al., 2016), and subsequently influencing C transformation enzyme activities to affect CH_4 emission; (2) enhanced UV-B radiation inhibits rice plant growth and decreases tiller numbers and the aerenchyma area in rice plants, thereby reducing the capacity of rice plants to transport and emit CH_4 in the rice field soil (Li et al., 2018). The current variables in this study remain limited in providing an exact explanation for the influencing processes of enhanced UV-B on CH_4 emission (path coefficient =0.15); more variables are needed to further study the relationships among enhanced UV-B, rhizospheric microorganisms and CH_4 emission. Furthermore, understanding the seasonal dynamics of UV-B and their driving mechanisms, and providing corresponding suggestions to management by stages could be essential goals for future study.

4.3 Challenges raised by enhanced UV-B and prospects for future research

Enhanced UV-B has reduced CH_4 emissions, but it does not mitigate GWP as a whole in the Yuanyang Terraces. In the rice-growing period, there is a trade-off between CH_4 and CO_2, with enhanced UV-B significantly reducing emissions of the former, while increasing emissions of the latter by 15.00%, to affect an increase in the mean value of GWP by 6.20% (Figure 4). This trade-off is in accordance with the finding from Huang et al., and can be explained by the conservation of matter and corresponding C transformation, which link to shifts in the rhizosphere soil oxidation-deoxidation environment, and can in turn be affected indirectly by enhanced UV-B (He et al., 2016; Zhu et al., 2019; Huang et al., 2021). However, contrasting results are observed in the winter fallow period. During this period, all mean values of CH_4, N_2O, and CO_2 emissions declined under the effect of enhanced UV-B, and a subsequently significant reduction in GWP is observed. This difference can be explained by the fact that enhanced UV-B affects rice metabolism and morphological characteristics to drive greenhouse gas emissions during the rice-growing period, while it drives emissions by affecting OH radicals and the decomposition rate of rice straws in the winter fallow period (Fenimore 1969; He et al., 2014; He et al., 2016; Zhou et al., 2018). In sum, different greenhouse gas emission processes and balancing mechanisms were observed between the winter fallow and rice-growing periods.

It is notable that enhanced UV-B not only leads to an increase in CO_2 emissions, but also reduces C sequestration in plant biomass and microbial biomass, which negatively and significantly affect rice plant biomass, rice yield, and rice seed weight (Figure 4; Section 6 in SI). This is because enhanced UV-B radiation is an environmental stress which can hinder plant metabolism, affect material composition (for example by increasing lignin and total phenols content), and reduce the total biomass accumulation of rice (Figure 4; Section 6 in SI). Furthermore, it also affects root exudates to further drive rhizosphere microbial communities and corresponding enzyme activities, and finally affect the C balance and rice yield in rice terraces (Lou, Zhou, and Ren 2012; Xu et al., 2015; He et al., 2016). Notably, when considering the effect of enhanced UV-B on greenhouse gas emissions, it is insufficient to only use the GWP index. Some studies have indicated that economically efficient trade-offs between CO_2, CH_4, and N_2O are also required when meeting a temperature stabilization target (Johansson, Persson, and Azar 2005; Zhu et al., 2019). The Yuanyang Terraces are located in an underdeveloped mountainous area in southwest China, targeted by China's poverty alleviation policy (Fullen et al., 2017; Liu, Liu, and Zhou 2017). In this study it is found that enhanced UV-B would increase CO_2 and N_2O emissions, and negatively affect rice yield and quality, which hinders regional food security and sustainable development. Therefore, integrating consideration of the mitigation of greenhouse gas emissions with a concern for food security, economic enhancement and corresponding trade-offs is a prospect for future research.

5 Conclusion

Yuanyang Terraces is one of the oldest and largest rice terraces in China. Its CH_4 emission intensity (18.10 mg/m^2/h) is significantly lower than those of other paddy fields subjected to prolonger flooding in southwest China, but remains significantly higher than the mean value in China. Weather conditions (27.02%) and the cultivation stage of rice (25.65%) were the predominant factors driving CH_4 emission from the terraces. Enhanced UV-B can reduce CH_4 emission both in the winter fallow period and the rice-growing period at similar reduction ratios (15.13% and 16.12%), but the pathways driving these reductions are different. In the winter fallow period, enhanced UV-B principally affected rice straw (the only organic matter input) and its decomposition, subsequently leading to a significant decline in both easily-oxidized C content in the soil (18.10%) and β-glucosidase activity (17.40%), and a reduction in CH_4 emissions from 11.91 to 10.10 mg/m^2/h in the rice terraces. During the rice-growing period, enhanced UV-B can affect rice root exudation and corresponding composition of rhizospheric microbes, meaning that changes in soil enzyme activities were the predominant factor in the reduction of CH_4 emissions. There is a trade-off between CH_4 and other greenhouse gas emissions during the rice-growing period. Enhanced UV-B reduced the rice terrace's CH_4 emission by 15.70%, but increased CO_2 and N_2O emissions, and negatively impacted rice yield and quality, which hinders regional food security and sustainable development. Integrating a consideration of the mitigation of greenhouse gas emissions with a concern for food security is a prospect for future research.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, YH and FZ; methodology, FZ and KY; software, writing—original draft preparation, KY; investigation, CW, ZL, and XL; data curation, ML; writing—review and editing, YH and FZ; supervision, YL; All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.1051006/full#supplementary-material

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