Effects of silicate application on CH$_4$ and N$_2$O emissions and global warming potentials in paddy soil under enhanced UV-B radiation

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Abstract
Enhanced ultraviolet-B (UV-B) radiation is induced by the depletion of the stratospheric ozone layer. Silicate is beneficial to rice growth and can increase the resistance of rice plant to UV-B radiation, but so far few reports have been available on whether silicate application can reduce CH$_4$ and N$_2$O emissions from paddy soils under enhanced UV-B radiation. A field experiment was conducted to investigate the effects of silicate application on CH$_4$ and N$_2$O emissions and global warming potentials (GWPs) under enhanced UV-B radiation in a paddy soil. The experiment with rice was designed with two UV-B radiation levels, that is, ambient UV-B (A, ambient) and enhanced UV-B radiation (E, enhanced by 20%); and two silicate application levels, that is, control (Si0, 0 kg SiO$_2$·ha$^{-1}$) and silicate application (Si1, 200 kg SiO$_2$·ha$^{-1}$). CH$_4$ and N$_2$O fluxes were determined by closed chamber method at one-week interval during rice growth period. The results show that, compared with ambient UV-B radiation, enhanced UV-B radiation clearly decreased the dry matter weights of shoot, root, and whole plant by 13.12%, 53.31%, and 25.85%, respectively, in the treatment without silicate application, and by 1.47%, 34.49%, and 11.12%, respectively, in the treatment with silicate application. Enhanced UV-B radiation significantly increased the flux and cumulative emission of N$_2$O and stimulated the GWPs of CH$_4$ and N$_2$O emissions and global warming potentials. Silicate application significantly reduced flux and cumulative emission of CH$_4$, promoted the flux and cumulative emission of N$_2$O, and reduced the GWPs of CH$_4$ and N$_2$O. This study suggests that silicate application can reduce the contribution of enhanced UV-B radiation to global warming potentials.

KEYWORDS
methane, nitrous oxide, rice, silicate application, UV-B radiation
1 INTRODUCTION

Enhanced ultraviolet-B (UV-B) radiation and climate warming are two important global environmental problems. In recent years, due to emissions of large quantities of chlorofluorocarbons (CFCs) and nitrogen oxides, the stratospheric ozone layer has been depleted and become thinner, leading to enhanced UV-B radiation to the Earth’s surface. Global climate warming is related to the emissions of greenhouse gases. Methane (CH₄) and nitrous oxide (N₂O) are two main greenhouse gases. At 100-year scale, the global warming potentials (GWPs) of CH₄ and N₂O are 28 and 265 times higher than CO₂, respectively. Paddy fields have been identified as major anthropogenic contributors to CH₄ and N₂O emissions, accounting for 12% of the total anthropogenic CH₄ budget.

Some researchers investigated the effects of enhanced UV-B radiation on greenhouse gas emissions, but mainly focused on CH₄ or N₂O. Enhanced UV-B radiation significantly increased CH₄ emission from rice fields, likely related to enhanced root exudation and aerobic CH₄ production in rice. Enhanced UV-B radiation decreased N₂O emission from soybean and winter wheat. However, few reports have been related to enhanced UV-B radiation effects on CH₄ and N₂O emissions in paddy fields.

Silicate is a beneficial nutrient for rice growth. Silicate application can promote rice growth and increase the resistance of rice plant to biological and non-biological stresses, such as diseases and insects, heavy metal pollutions and UV-B radiation. Iron slag, a byproduct of the steel industry, contains high amount of active iron oxide and silicate and is commonly used as a slag-type silicate fertilizer. Slag-type silicate fertilization could increase rice yield and suppress CH₄ emission by 5%-49% in paddy soils. Application of slag-type silicate fertilizer led to increase in soil Fe⁺⁺ concentration, resulting in enhancing the activity of iron-reducing bacteria, and correspondingly depressing the activity of methanogenesis, as competing for zymolyte and electron donor. Application of slag fertilizer particles decreased the bulk weight of soil, and increased the porosity, and thus possibly enhanced the oxygen inflow amount from atmospheric environment. Amendment of slag silicate fertilizer also increased soil pH and Eh, leading to suppression of methanogenic activity. In addition, silicate application promoted rice root growth, thus leading to increase in root oxygen exudation, enhancement of methanotrophic activity, depression of methanogenic activity, and reduction in CH₄ emission. In contrast, it is still unclear how slag-type silicate fertilization affected N₂O production and emission in paddy soils. Some researchers found that adding slag silicate fertilizer decreased N₂O emission in paddy soils. However, others reported that slag fertilizer application increased N₂O emission or had no effects on N₂O emission in paddy soils.

Silicate fertilizers include silicate fertilizers with iron (eg, slag-types) and those without iron (eg, silicate-types). So far, most reports have focused on slag-type fertilizers, especially iron (Fe³⁺) role in mitigating CH₄ emission, but few researches have been concerned with the application of silicate fertilizers without iron or only adding silicate effects on CH₄ and N₂O emissions. Our previous study indicated that elevated UV-B radiation could increase CH₄ emission, but silicate application significantly decreased CH₄ emission in a paddy soil. However, few reports have been available concerning the coupled effects of silicate application with enhanced UV-B radiation on the emissions of CH₄ and N₂O from paddy fields. The purposes of this study are to investigate the effects of silicate application on CH₄ and N₂O emissions and the GWPs in a Chinese paddy soil under enhanced UV-B radiation and to provide reference for further developing new measures to mitigate greenhouse gas emissions from paddy fields.

2 MATERIALS AND METHODS

2.1 Experimental design

A field experiment was carried out at the Station of Agricultural Meteorology, Nanjing University of Information Science and Technology (32.16°N, 118.86°E) from May to November 2015. This station is located in the northern subtropical humid climate zone, with mean annual precipitation of 1000-1100 mm and mean annual temperature of 15.6°C. The tested rice cultivar was Oryza sativa L. cv Nanjing 46. The tested silicate fertilizer was sodium silicate, with 49.2% of available silicon (SiO₂). The tested soil was hydromorphic paddy soil, classified as a Typic Stagnic Anthrosol (Soil Taxonomic Classification Research Group of China, 1993). The soil texture was loamy clay. The soil contained 19.4 g·kg⁻¹ of total organic carbon, 1.45 g·kg⁻¹ of total nitrogen, 95 mg·kg⁻¹ of available Si, 261 g·kg⁻¹ of clay content (<1 mm), and 6.2 of pH value (soil : water ratio 1:1).

The experiment was designed with two factors, that is, UV-B radiation intensity and silicate application. UV-B radiation intensity was set at two levels, that is, control (A, ambient UV-B radiation, 12.0 kJ·m⁻²·day⁻¹) and 20% above the control (E, enhanced UV-B radiation, diurnal mean UV-B radiation of 14.4 kJ·m⁻²·day⁻¹). The dosage of elevated UV-B radiation corresponded to approximately 25% stratospheric ozone depletion in Nanjing, China (32° 3’ N, 118° 46’ E) using the model of Green. The enhanced UV-B level was supplied with UV light tubes made of quartz glass (HQ 40 W, Nanjing, China). The radiation emitted by the UV tubes ranged from 280 to 400 nm, peaking at 303 nm. An elevatable stand was used to support the UV light tube over rice canopy to simulate enhanced UV-B radiation. In the enhanced UV-B treatment, the light tubes were wrapped with cellulose acetate film to filter out wavelengths below 280 nm (UV-C).
treatment, those tubes were wrapped with a polyester plastic film to remove all radiations below 320 nm (UV-B+UV-C) (Figure 1). Thus, the UV-B treatment only elevated the UV-B radiation, whereas all other conditions were same as the control. The silicate application had two levels, that is, reference (Si0, 0 kg SiO2/hm2) and silicate application (Si1, 200 kg SiO2/hm2). Rice plants were subjected to four treatments, that is, (1) enhanced UV-B radiation + silicate application (E+Si1), (2) enhanced UV-B radiation + no silicate application (E+Si0), (3) ambient UV-B radiation + silicate application (A+Si1), and (4) ambient UV-B radiation + no silicate application (A+Si0). Each treatment was replicated three times and randomly distributed to minimize positional effects on rice growth. The plot size was 2 m x 2 m = 4 m².

Rice seeds were sterilized with 10% H2O2 solution (v/v) for 5 min, washed with deionized water, and sowed into seeding bed on 10 May 2015. Rice seedlings were transplanted into paddy field on 13 June, with planting spacing of 16 cm x 23 cm. One day before transplanting, 315 g of composted rice straw was applied to each plot, equivalent to 200 kg·ha⁻¹ nitrogen (N), 200 kg·ha⁻¹ phosphorus (P2O5), and 200 kg·ha⁻¹ potassium (K2O), respectively. In addition, 183 g of sodium silicate was applied to the plots with silicate application (Si1), equivalent to 200 kg·ha⁻¹ silicate (SiO2). The above fertilization levels (NPK; Si) are usually adopted in rice production at the Yangtze River Delta of China. UV-B treatment was started at tillering stage (the 25th day after transplanting) until maturity. The distance between UV-B light source and rice canopy always maintained at 0.8 m. The plants were treated with UV-B irradiation for 8 hours per day (from 8:00 to 16:00), excluding cloudy and rainy days, until rice maturity. The supplemental dose of UV-B was modulated by turning off 25% of the lamps in the morning (8:00-9:30) and afternoon (around 3:00-4:00) on sunny days. The field was drained and dried from August 15 to 1 September 2015. Diseases and pests were controlled by traditional management programs, according to actual field situations. The filed water layer during rice-growing season was maintained at about 5 cm in depth, and reasonable irrigation was implemented based on water layer change and rainfall status.

2.2 | Gas sampling and measurement

Gas samples were taken from the field using the closed chamber method. Prior to transplanting, the chamber base was inserted and fixed into the soil, two seedlings uniform in size were transplanted inside the base. Gas sampling was conducted from 8:00 to 11:00 at one-week interval from tillering to maturity, and meanwhile air temperature inside the chamber was recorded. In sampling, the chamber was placed onto the base fixed into the soil in advance, and then, the chamber bottom was immersed in water layer to ensure gas tightness. Before collecting gas samples, the mini-fan fixed on the ceiling of the chamber was turned on for 20 seconds to mix the gas in the chamber, and then, gas samples were extracted using syringes with a tee valve at 0, 15, and 30 min, respectively. The samples were injected into pre-evacuated bottles (50 mL). Methane and N2O concentrations in the samples were detected with a gas chromatograph (Agilent 7890B), equipped with a flame ionization detector (FID) and an electron capture detector (ECD), and packed with Porapak Q column (G3591-81013). The temperatures for column, injector, and detector were set at 50, 200, and 200°C. Nitrogen and H2 gases were used as carrier and burning gases, respectively. The flow rates were set at 400 mL min⁻¹ for pure air and 45 mL min⁻¹ for H2 gas, respectively.

The equation for calculating CH4 and N2O fluxes is

\[ F = \rho \cdot H \cdot [\frac{273}{(273 + T)}] \cdot \frac{dc}{dt} \]

where \( F \) is flux (mg·m⁻²·h⁻¹); \( \rho \) is gas density under standard conditions (the densities of CH4 and N2O are 0.714 kg/m³ and 1.25 kg/m³, respectively); \( H \) is the chamber height (m); \( T \) is mean air temperature in the chamber during sampling (°C); and \( dc/dt \) is the slope of the concentration-time regression curve of a gas of interest in the chamber.

The calculation equation of cumulative CH4 and N2O emissions at growth stages is \( T = \sum [(F_{i+1} + F_i)/2] \cdot (D_{i+1} - D_i) \cdot 24 \) where \( T \) is the cumulative gas emission (mg/m²); \( F_i \) and \( F_{i+1} \) are the mean gas emission fluxes at the \( i \)th sampling and the \((i + 1)\)th sampling, respectively, mg·m⁻²·h⁻¹; \( D_i \) and \( D_{i+1} \) are the sampling time points at the \( i \)th sampling and the \((i + 1)\)th sampling, respectively, (d).

2.3 | Biomass determination

The sampling was conducted at rice maturity. Three representative plants were selected randomly from each plot. The
shoots were collected, and the root were dug out of the soil, and washed with tap water. The samples were immediately ovened at 105°C for 20 minutes and then were dried to constant weight in a drying oven at 70°C.

2.4 | Estimation of GWP

Global warming potential (GWP) was a parameter used to evaluate the relative potential effect of greenhouse gases on climate change. At a 100-year scale, the GWPs of CH₄ and N₂O were 28 and 265 times higher than that of CO₂, respectively. Therefore, the GWPs of CH₄ and N₂O emissions from paddy soil were calculated by multiplying the cumulative CH₄ and N₂O emissions over the whole growth period by 28 and 265 to obtain the CO₂ equivalents of cumulative CH₄ and N₂O emissions.

2.5 | Data processing and analysis

The experimental data were processed and plotted with Microsoft Excel 2010 software, and statistical analysis was conducted with SPSS21.0 software. Multiple comparison test was carried out among the treatments using the least significant difference method (LSD). Different letters in one column indicate significant difference between the treatments ($P < 0.05$). The * in a figure denotes significant difference at $P < 0.05$.

3 | RESULTS

3.1 | Biomass

Table 1 indicates that, regardless of silicate application, enhanced UV-B radiation significantly reduced root dry matter weight and total dry matter weight in rice and also decreased shoot dry matter weight, but the decrease was not significant ($P < 0.05$). In the treatment with silicate application, enhanced UV-B radiation significantly decreased the root and total dry weights by 34.49% and 11.12%, respectively. In the treatment without silicate application, enhanced UV-B radiation significantly decreased the root and total dry weights by 53.31% and 25.85%, respectively. The decrease in rice root dry weight under enhanced UV-B radiation was larger than that under ambient UV-B radiation, indicating that enhanced UV-B radiation had stronger effect on rice root system than ambient UV-B radiation. Under enhanced UV-B radiation, silicate application significantly increased rice shoot, root, and total dry weights by 61.30%, 43.74%, and 55.74%, respectively. In contrast, under ambient UV-B radiation, silicate application significantly increased rice shoot, root, and total dry weights by 44.69%, 26.11%, and 37.52%, respectively. Thus, the accumulation of shoot and root dry matters of rice was evidently reduced by enhanced UV-B radiation, but significantly promoted by silicate application, in favor of alleviating the depressive effects of enhanced UV-B radiation on the accumulation of rice dry matters.

### Table 1

| Treatment/Interaction | Shoot dry weight/g | Root dry weight/g | Whole-plant dry weight/g |
|-----------------------|--------------------|-------------------|--------------------------|
| E + Si1               | 16.19 ± 1.07a      | 6.69 ± 2.03b      | 22.88 ± 2.79b            |
| E + Si0               | 10.04 ± 2.43b      | 4.65 ± 0.55c      | 14.69 ± 3.96d            |
| A + Si1               | 16.42 ± 2.81a      | 8.99 ± 3.07a      | 25.41 ± 3.39a            |
| A + Si0               | 11.35 ± 1.24b      | 7.13 ± 2.68b      | 18.48 ± 2.96c            |

| Note: A: ambient UV-B; E: enhanced UV-B; Si0: control; Si1: silicate application. Different letters in one column indicate significant difference between the treatments ($P < 0.05$). *Significant difference among the variables ($P < 0.05$), ns means no significance. The same as below.

#### 3.2 | CH₄ emission flux

The seasonal variations of CH₄ emission from paddy soil were basically consistent in different treatments (Figure 2). CH₄ emission fluxes were relatively low at early tillering stage, increased gradually later, and reached a peak on the 55th day after transplanting (tillering stage); declined sharply afterward and maintained at relatively low level from the 76th day after transplanting (jointing-booting stage) until maturity. At early tillering stage, although the field had been submerged in water, occluded oxygen likely existed in soil, so the soil still did not form anaerobic environment, plant biomass at seedling stage was relatively low; thus, CH₄ emission was also relatively low. With extending water immersion time, extremely anaerobic environment was formed, more rice tillers produced, and root exudates increased; thus, the activity of methanogens was promoted, CH₄ emission...
increased accordingly, reaching a peak on the 55th day after transplanting. The field drying started on the 58th day after transplanting, as drying improved oxygen supply in the soil, CH$_4$ fluxes declined sharply.

Over the whole growth period, irrespective of silicate application, enhanced UV-B radiation increased CH$_4$ fluxes from paddy soil. From the 27th day to the 55th day after transplanting (tillering stage), under silicate application, CH$_4$ fluxes with enhanced UV-B radiation were 467.41%, 510.31%, 183.95%, 30.77%, and 36.55% higher than those with ambient UV-B radiation, respectively. Under no silicate application, CH$_4$ fluxes with enhanced UV-B radiation were 279.86%, 212.67%, 200.33%, 72.08%, and 64.41% higher than those with ambient UV-B radiation, respectively. Irrespective of enhanced UV-B radiation, silicate application significantly decreased CH$_4$ fluxes from paddy soil. At tillering stage, CH$_4$ fluxes with silicate application were lower than those without silicate application. Under ambient UV-B radiation, CH$_4$ fluxes with silicate application were 75.33%, 65.88%, 39.82%, 9.91%, and 14.47% lower than those without silicate application, respectively. Under enhanced UV-B radiation, CH$_4$ fluxes with silicate application were 63.15%, 33.41%, 43.09%, 31.53%, and 28.96% lower than those without silicate application, respectively. The above results indicate that enhanced UV-B radiation significantly increased CH$_4$ emission, whereas silicate application evidently alleviated the promotive effect of enhanced UV-B radiation on CH$_4$ emission from paddy soil.

### 3.3 | Cumulative CH$_4$ emission

Among the selected four growth stages, tillering stage had the highest cumulative CH$_4$ emission, accounting for about 80% of total emission, followed by jointing-booting stage, with cumulative CH$_4$ emission accounting for about 18% of total emission, heading-flowering stage and grain filling-maturity stage had the lowest cumulative CH$_4$ emission, each accounting for only about 1% of total emission (Table 2). Under silicate application, enhanced UV-B radiation increased cumulative CH$_4$ emissions at tillering stage, jointing-booting stage, heading-flowering stage and grain filling-maturity stage, and over the whole growth period by 44.86%, 18.71%, 10.11%, 4.23%, and 38.62%, respectively. Under no silicate application, enhanced UV-B radiation increased the cumulative CH$_4$ emissions by 101.65%, 63.12%, 13.96%, 3.94%, and 89.43%, at the above four growth stages and over the whole growth period, respectively. Significant effects of enhanced UV-B radiation on cumulative CH$_4$ emissions occurred at tillering stage, jointing-booting stage, and over the whole growth period ($P < 0.05$).

Silicate application significantly reduced the cumulative CH$_4$ emission from paddy soil in most cases ($P < 0.05$). Under ambient UV-B radiation, the cumulative CH$_4$ emissions with silicate application at the above four growth stages, and over the whole growth period were 25.74%, 37.74%, 10.54%, and 48.32% lower than those without silicate application, respectively. Under enhanced UV-B radiation, the cumulative CH$_4$ emissions with silicate application at the above four growth stages and over the whole growth period were 35.83%, 45.96%, 39.84%, 10.29%, and 38.41% lower than those without silicate application, respectively.

In brief, enhanced UV-B radiation significantly promoted CH$_4$ emission from paddy soil, with significant differences between treatments at tillering stage and jointing-booting stage ($P < 0.05$), whereas silicate application significantly decreased CH$_4$ emission, with significant differences between treatments at most stages, except grain filling-maturity stage ($P < 0.05$). Over the whole growth period, silicate application had significantly suppressive effect on CH$_4$ emission from paddy soil under enhanced UV-B radiation ($P < 0.05$).
3.4 | N$_2$O emission flux

N$_2$O flux was relatively low at tillering stage, exhibiting irregular variation, started to rise gradually on the 55th day after transplanting (tillering stage), and reached the first peak on the 69th day after transplanting (jointing-booting stage); afterward declined, and reached to its minimum on the 90th day after transplanting (jointing-booting stage); reached the second peak on the 97th day after transplanting (heading-flowering stage); declined sharply later, and rose again from the 132nd day to the 139th day after transplanting (grain filling-maturity stage) (Figure 3).

Over the whole growth period, N$_2$O flux increased under enhanced UV-B radiation. From the 62nd day to the 83rd day after transplanting (jointing-booting stage), under silicate application, N$_2$O fluxes with enhanced UV-B radiation were 30.89%, 53.35%, 109.04%, and 137.48% higher than those with ambient UV-B radiation, respectively; under no silicate application, N$_2$O fluxes with enhanced UV-B radiation were 83.01%, 0.91%, 171.51%, and 89.03% higher than those with ambient UV-B radiation, respectively. On the 97th day after transplanting (heading-flowering stage), under silicate application, N$_2$O flux with enhanced UV-B radiation was 102.92% higher than that with ambient UV-B radiation; under no silicate application, N$_2$O flux with enhanced UV-B radiation was 151.31% higher than that with ambient UV-B radiation. From the 132nd day to the 139th day after transplanting (grain filling-maturity stage), under silicate application, N$_2$O fluxes with enhanced UV-B radiation were 165.79% and 22.98% higher than those with ambient UV-B radiation; under no silicate application, N$_2$O fluxes with enhanced UV-B radiation were 143.63% and 93.99% higher than those with ambient UV-B radiation.

Silicate application had different effects on N$_2$O fluxes from paddy soil at different growth stages. From the 62nd day to the 83rd day after transplanting (jointing-booting stage), silicate application increased N$_2$O fluxes. Under ambient UV-B radiation, N$_2$O fluxes with silicate application were 159.41%, 11.15%, 100.83%, and 59.17% higher than those without silicate application; under enhanced UV-B radiation, N$_2$O fluxes with silicate application were 85.55%, 68.92%, 54.62%, and 99.97% higher than those without silicate application. On the 97th day after transplanting (heading-flowering stage), silicate application reduced N$_2$O fluxes from paddy soil. Under ambient UV-B radiation, N$_2$O flux with silicate application was 19.45% lower than that without silicate application; under enhanced UV-B radiation, N$_2$O flux with silicate application was 35.01% lower than that without silicate application. From the 132nd day to the 139th day after transplanting (grain filling-maturity stage), silicate application caused an increase in N$_2$O fluxes from paddy soil. Under ambient UV-B radiation, N$_2$O fluxes with silicate application were 30.78% and 126.81% higher than those without silicate application; under enhanced UV-B radiation,
N$_2$O fluxes with silicate application were 42.68% and 43.79% higher than those without silicate application. The above results revealed that enhanced UV-B radiation increased N$_2$O emission from paddy soil, while silicate application promoted N$_2$O emission from paddy soil at jointing-booting stage and grain filling-maturity stage, but reduced N$_2$O emission at heading-flowering stage.

### 3.5 Cumulative N$_2$O emission

Among the selected four growth stages, the highest cumulative N$_2$O emission occurred at jointing-booting stage, accounting for about 50% of total emission, followed by heading-flowering stage with cumulative CH$_4$ emission, accounting for about 24% of total emission, tillering stage with cumulative N$_2$O emission, accounting for about 15% of total emission, and grain filling-maturity stage with the lowest cumulative CH$_4$ emission, accounting for only about 11% of total emission (Table 3).

Over the whole growth period, regardless of silicate application, enhanced UV-B radiation significantly increased the cumulative N$_2$O emission from paddy soil. Under silicate application, enhanced UV-B radiation significantly increased the cumulative N$_2$O emissions at the selected growth stages and over the whole growth period by 44.86%, 58.91%, 44.09%, 60.08%, and 54.07%, respectively, compared with ambient UV-B radiation. Under no silicate application, enhanced UV-B radiation significantly increased the cumulative N$_2$O emissions at the selected growth stages and over the whole growth period by 69.89%, 41.62%, 134.57%, 84.46%, and 73.69%, respectively, compared with ambient UV-B radiation. Silicate application effect on the cumulative N$_2$O emission differed with growth stage, with significant differences in most cases ($P < 0.05$). Under ambient UV-B radiation, the cumulative N$_2$O emissions with silicate application at tillering stage was 2.15% lower than that without silicate application, and those at the jointing-booting stage, heading-flowering stage and grain filling-maturity stage, and over the whole growth period were 49.78%, 9.11%, 41.84%, and 14.90% higher than those without silicate application, respectively. Under enhanced UV-B radiation, the cumulative N$_2$O emissions with silicate application at tillering stage and heading-flowering stage were 16.57% and 32.97% lower than those without silicate application, respectively; however, those at jointing-booting stage and grain filling-maturity stage, and over the whole growth period were 68.06%, 23.09%, and 29.53% higher than those without silicate application, respectively. In general, silicate application significantly stimulated N$_2$O emission from paddy soil, especially under enhanced UV-B radiation over the whole growth period, with significant interaction effects (UV-B, silicate application) on the cumulative N$_2$O emission in the paddy soil ($P < 0.05$).

### 3.6 Global warming potentials

Enhanced UV-B radiation significantly increased the GWP of CH$_4$ or N$_2$O cumulative emission in the paddy soil. Irrespective of silicate application, the GWP of CH$_4$ or N$_2$O cumulative emission under enhanced UV-B radiation was significantly higher than that under ambient UV-B radiation. In contrast, silicate application significantly reduced the GWP of CH$_4$ or N$_2$O cumulative emission in the soil. The GWP of CH$_4$ or N$_2$O cumulative emission under silicate application was significantly lower than that under no silicate application. Furthermore, enhanced UV-B radiation significantly increased the GWPs of combined CH$_4$ and N$_2$O cumulative emission, while silicate application significantly reduced the contribution of enhanced UV-B radiation to global greenhouse effect ($P < 0.05$).
DISCUSSION

Plant biomass reflects the effect of environmental factors on plant growth. This study shows that enhanced UV-B radiation decreased shoot and root biomass of rice and suppressed rice growth (Table 1). The reason is that UV-B radiation damaged photosystem II, reduced its activity, and suppressed photosynthesis, thereby affected rice growth. Furthermore, UV-B radiation suppressed the synthesis of endogenous substances in rice, unfavorable for shoot and root growth. Silicate application led to an increase in shoot and root biomass of rice, promoting rice growth, and alleviating the adverse effect of enhanced UV-B radiation. On the one hand, silicate application was favorable for rice to resist the damage by UV-B radiation, on the other hand, silicate application could regulate plant metabolism in rice, stimulating the synthesis of phenols in leaves to resist UV-B radiation. Therefore, silicate application effectively alleviated the suppressive effect of UV-B radiation on rice growth.

Enhanced UV-B radiation significantly increased the flux and cumulative emission of CH\(_4\) from paddy soil (Figure 2 and Table 2). In contrast, other studies showed that enhanced UV-B radiation had no significant effect on CH\(_4\) emission from paddy soil. The reason may be that CH\(_4\) emission from paddy soil was affected by such factors as soil physico-chemical properties, water and fertilizer management and climate. Different experimental conditions likely led to different results. Therefore, studies are necessary to investigate whether increased soil pH value affected the generation of methane or not.

| Treatment/Interaction | Whole growth period |
|-----------------------|---------------------|
|                       | Emission/(mg/m\(^2\)) | Percent/% | Emission/(mg/m\(^2\)) | Percent/% | Emission/(mg/m\(^2\)) | Percent/% | Emission/(mg/m\(^2\)) | Percent/% |
| E+Si1                 | 26.45 ± 3.60ab       | 13.16     | 112.77 ± 12.75a       | 56.11     | 38.17 ± 4.90b         | 18.99     | 23.60 ± 4.58a         | 11.74     |
| E+Si0                 | 31.70 ± 2.63a        | 18.12     | 67.10 ± 3.20b         | 38.36     | 56.95 ± 5.52a         | 32.56     | 19.17 ± 2.98b         | 10.96     |
| A+Si1                 | 18.26 ± 3.58b        | 14.00     | 70.96 ± 6.76b         | 54.40     | 26.49 ± 4.25c         | 20.31     | 14.74 ± 6.54c         | 11.30     |
| A+Si0                 | 18.66 ± 9.46b        | 18.53     | 47.38 ± 2.77c         | 47.04     | 24.28 ± 0.24c         | 24.11     | 10.39 ± 1.56d         | 10.32     |
| Si ns                 | *                    |           | *                    |           | *                    |           | *                    |           |
| UV-B *                | *                    |           | *                    |           | *                    |           | *                    |           |
| UV-BxSi *             | *                    |           | *                    |           | *                    |           | *                    |           |

*Significant difference at P < 0.05.
texture, physical protection by clay particles decreased the decomposition of organic matter; and relatively weak gas diffusion in clayey soil was unfavorable for CH4 diffusion; in addition, clayey soil had strong buffer capacity, in favor of maintaining high redox potential.35

The field drying started on the 58th day after transplanting, as drying improved soil aeration and stimulated N2O generation, N2O flux reached a peak. The field drying ended and the field was reflooded on the 73rd day after transplanting, so N2O flux declined gradually to the minimum, but reached the second peak on the 97th day after transplanting (heading‐flowering stage). The reason was related to that, heading‐flowering stage was in the rainy season with temperature declining, suitable for nitrification and denitrification, and thus in favor of N2O generation and emission. Over late growth period, N2O flux started to rise again, because irrigation stopped before harvest, soil surface dried up and anaerobic environment was destroyed.36 The cumulative N2O emission was mainly concentrated at jointing‐booting stage, and the possible reason was concerned with that field drying at this stage improved soil aeration and stimulated N2O production and emission.26 Enhanced UV‐B radiation significantly increased the flux and cumulative emission of N2O from paddy soil (Figure 3 and Table 3). N2O emission is mainly produced from the microbial processes of nitrification and denitrification in paddy soil; enhanced UV‐B radiation significantly increased available nitrogen, microbial biomass carbon and nitrogen, and raised carbon-to-nitrogen ratio in rhizospheric soil, to provide substrate and energy for nitrification and denitrification, thereby promoted N2O emission from paddy soil. Some researchers reported that enhanced UV-B radiation had no significant effect on N2O flux from rice and winter wheat fields.28 In contrast, other researchers released that enhanced UV-B radiation significantly decreased plant biomass, affected nitrogen metabolism, and reduced N2O emission from soybean field.10 More studies showed that the susceptibilities of crops to UV-B radiation varied with crop types and species.40,41 In addition, water and fertilization also largely affected N2O emission.42,43 The different results mentioned above are likely related to such different factors as crop types, soil physical and chemical properties, as well as water and fertilization managements. In this study, silicate application promoted N2O emission from rice soil, the reason may be related to that silicate application simulated the rigidity of rice aerenchyma, improved oxygen transport capability in plant and oxidizing capability in root system, activated peroxidase and increased redox potential (Eh) in soil, and thus promoted nitrification.17 The emissions of N2O and CH4 from paddy soil showed trade‐off relationship.42 Similar result was also observed in this study, namely silicate application reduced CH4 emission but stimulated N2O emission from paddy soil.

Enhanced UV-B radiation significantly increased CH4 and N2O fluxes and cumulative emissions of CH4 and N2O from paddy soil. Silicate application could reduce CH4 emission while promote N2O emission from paddy soil. Global warming potentials (GWP) were used to investigate whether silicate application alleviated the combined greenhouse effect of CH4 and N2O emissions from paddy soil. Enhanced UV-B radiation significantly increased the GWPs of CH4 and N2O emissions from paddy soil. Global warming potentials (GWP) were used to investigate whether silicate application alleviated the combined greenhouse effect of CH4 and N2O emissions from paddy soil. Enhanced UV-B radiation significantly increased the GWPs of CH4 and N2O emissions from paddy soil, while silicate application evidently alleviated the contribution of enhanced UV-B radiation to the GWPs (Table 4). Further researches are needed to investigate the effects of silicate fertilizer types, fertilization levels and methods on CH4 and N2O emissions from paddy soil under enhanced UV-B radiation.

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| Treatment/Interaction | CH4 \(\text{GWP/(kg/hm}^2\) \pm SE \% | N2O \(\text{GWP/(kg/hm}^2\) \pm SE \% | Combined GWP of CH4 and N2O/(kg/hm2) \pm SE |
|-----------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| E+Si1                 | 774.76 ± 6.44b 59.26                   | 553.62 ± 16.24a 40.74                  | 1307.38 ± 22.68b                      |
| E+Si0                 | 1237.33 ± 10.47a 72.75                 | 463.54 ± 36.09b 27.25                  | 1700.87 ± 46.57a                      |
| A+Si1                 | 558.89 ± 7.41d 61.78                   | 345.69 ± 52.44c 38.22                  | 904.58 ± 59.85c                       |
| A+Si0                 | 653.19 ± 14.34c 70.99                  | 266.88 ± 24.35d 29.01                  | 920.07 ± 38.69c                       |
| Si                    | *                                      | *                                      | *                                      |
| UV-B                  | *                                      | *                                      | *                                      |
| UV-B×Si              | *                                      | *                                      | *                                      |

Note: GWP means global warming potentials.
*Significant difference at \(P < 0.05\).
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