In the Field

GREENHOUSE GASES SCIENCE AND TECHNOLOGY

Controlling light quality and intensity can reduce N_2O and CO_2 emissions of mature aging rice

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Abstract: N_2O, CO_2, and CH_4 are important greenhouse gases (GHGs) in paddy fields, and rice plants play an important role in GHG emissions in paddy fields. However, the relationship between light and rice plant GHG emissions is unclear. In this study, we monitored N_2O, CO_2, and CH_4 emissions of mature aging rice under different light qualities and intensities. The results showed that (i) under natural sunlight, the rice phyllosphere N_2O emission rate was 22.94 μg pot^{-1} h^{-1}, accounting for 60% of the whole rice plant total N_2O-N evaporation loss. The CO_2 emission rates from the phyllosphere and the root system were 27.82 mg pot^{-1} h^{-1} and 8.02 mg pot^{-1} h^{-1}, respectively. However, no CH_4 net emission effects were observed. (ii) Under a constant LED monocolor light intensity (1600 Lux), red, blue, and white light can inhibit N_2O and CO_2 emissions from the rice phyllosphere, resulting in lower emissions than yellow light. White light can also inhibit N_2O and CO_2 emissions from rice roots. (iii) Within the range of 0-6000 Lux, increases in light intensity can reduce rice phyllosphere CO_2 emissions, but such increases also promote N_2O emissions from the rice phyllosphere and the roots. In contrast, natural sunlight can promote rice phyllosphere N_2O and CO_2 emissions and can inhibit root N_2O emissions. The measure of light control may be the key to low-carbon technology for GHG emission reductions in mature paddy ecosystems. © 2015 Society of Chemical Industry and John Wiley & Sons, Ltd

Keyword: GHG emissions; light quality; light intensity; paddy field; liquid culture medium

Introduction

N_2O, CO_2, and CH_4 are the most important GHGs in the atmosphere and contribute nearly 80% of the greenhouse effect.[1] Paddies are considered one of the important sources of atmospheric CH_4 and N_2O, accounting for approximately 5% to 19% of total global CH_4 emissions.[2] Therefore, the effect of GHG emissions in paddy fields has become the focus of researchers studying agricultural GHG emissions. Presumably, 90% of soil N_2O emissions come from nitrification and denitrification.[3] Under flooded conditions, paddy soil denitrification occurs violently, causing a large amount of production of and emission of N_2O.[4] Combined with the advantages of carbon-rich organic matter, nitrogen fertilizer in paddy soils can significantly increase N_2O emissions.[5] Some studies have shown that CO_2 emissions are mainly

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Received June 21, 2015; revised September 8, 2015; accepted September 8, 2015
Published online at Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ghg.1565

from the decomposition of soil organic matter by paddy soil microbes.[6,7] and are affected by air temperature, soil temperature, and soil permeability. Within a certain range, nitrogen fertilizer provides ample nitrogen for soil microbes[8] and promotes the proliferation of micro-organisms and the decomposition of organic matter, thus contributing to soil CO_2 emissions.

Some studies have indicated that CH_4 emissions are mainly attributable to soil-related methanogen bacteria, which use CO_2/H_2 and an acetate (CH_3COO^-) matrix in a reduction process under extreme anaerobic conditions (usually Eh ≤ –200 mv)[9]. When a paddy field is flooded, the reducing anaerobic environment is highly conducive to CH_4 production. Thus, the anthropogenic paddy ecosystem is one of the major emissions sources for atmospheric CH_4.[2] Its soil characteristics and physical and chemical properties,[10] climate factors, and fertilizer management can all affect emissions from this ecosystem.

In addition to paddy soil GHG emissions, the role of the rice plant itself is also a topic of interest. Previous studies noted that some N_2O volatilization occurs in the above-ground part of the rice plant, and light and nitrogen sources have significant impacts on N_2O emissions from the above-ground rice plant.[11,12] The rice roots are also an important source of N_2O emissions.[13] The rice plant volatilizes N_2O primarily through channel effector mechanisms.[14,15] For CO_2, some studies have shown that the apparent soil respiration rate was, on average, 3.31 times higher than the soil heterotrophic respiration during the rice growing season,[16] and that the rice plants and their root respiration can also produce high levels of CO_2 emissions.[17] Organic fertilizer, especially rice straw that is returned to the field, can increase CO_2 emissions significantly in a paddy because it increases rice root respiration.[18] Paddy CO_2 emissions include CO_2 from the respiration of rice roots and above-ground rice plants. The rice plants also play a very important role in paddy CH_4 emissions, with a contribution ratio of approximately 83–84%.[15]

It is generally agreed that the paddy ecosystems are important sources of CO_2, CH_4, and N_2O emissions, and rice plants have played a very important role in GHG emissions. However, the majority of studies have been conducted separately on rice plants or roots, and integrated monitoring and study of their GHG emissions is still relatively rare for the above- and below-ground parts of rice plants. Light, as the initial source of energy, has a great impact on rice plant nitrogen and carbon absorption and utilization, and it certainly affects the CH_4, N_2O and CO_2 emissions of the rice phyllosphere and the roots. Although the mature aging period is a period of strong respiration for plants and an important period for paddy GHG emissions, the effect of light quality and intensity on CH_4, N_2O, and CO_2 emissions of the rice phyllosphere and the roots in this life stage has not been thoroughly investigated. Light-emitting diodes (LEDs) can be controlled to achieve a light source spectrum,[25–27] produce a single wavelength of light, and solve the problem of impure light quality. In the present work, we studied the relationship between light quality and intensity and CH_4, N_2O and CO_2 emissions from the rice phyllosphere and the roots in the mature aging stage. This work aims to clarify the contribution of mature aging rice plants to CH_4, N_2O and CO_2 emissions while parsing the light control mechanism to provide a scientific explanation for how light-control technology affects paddy GHG emissions.

Materials and methods

Self-designed integrated GHG monitoring box

The self-designed integrated GHGs monitoring box is shown in Fig. 1. The monitoring box consisted of two main parts: the outer chamber (a cube, 30 cm × 30 cm × 100 cm) and the inner chamber (a cylinder, Φ25 cm × 50 cm). The inner chamber was nested within the outer chamber, and the materials were all made of plexiglass. The outer chamber was equipped with two small fans at the top for mixing air, and LED lamps were placed at regular intervals on the interior walls. The light intensity could be adjusted by controlling the number of opened and closed lamps. An Ø10 cm hole was located in the underside of the inner chamber. A miniature fan was installed on the removable roof to mix the air in the inner chamber. The inlet pipes and the exhaust pipes of the inner and outer chambers were connected with air pumps for gas sampling.

Rice plant preparation

The tested rice (*Oryza sativa* L.) cultivar was PeiZa TaiFeng (offered by South China Agricultural University). Rice seedlings were grown with the soil culture method, and rice plants were grown in nutrient solution culture using a hydroponics method. The

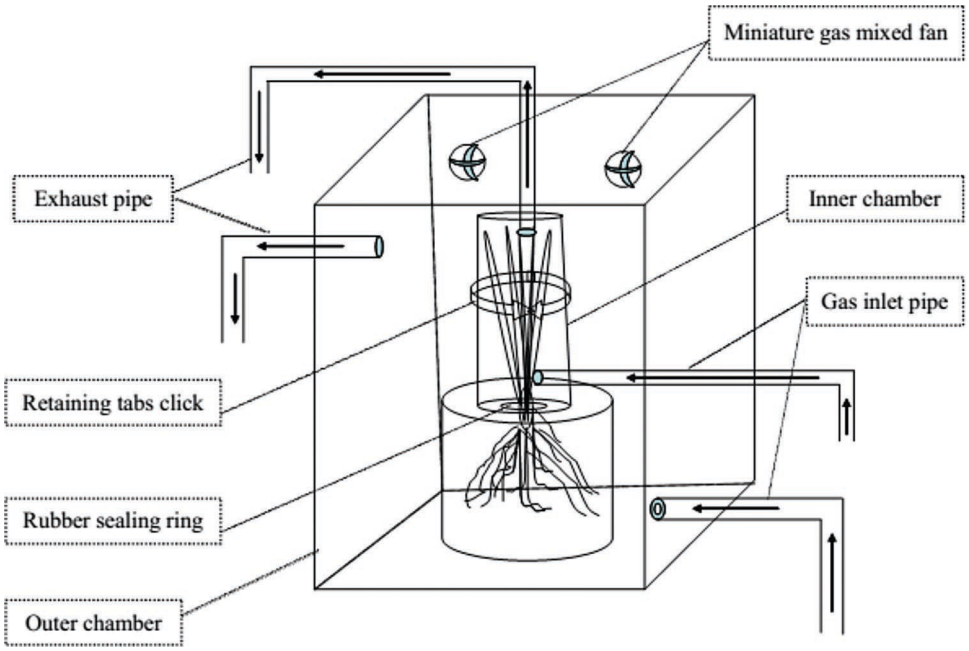

Figure 1. Self-designed integrated GHG monitoring box.

nutrient solution was changed weekly (6 L/ 1 plant) following the method described by Xu.[12]

Treatment with different weak light qualities and intensities

In this experiment, we used natural sunlight as CK and used different colors from weak LED bulbs to simulate different weak light quality and intensity environments. The colors included yellow, green, white, red, and blue, with three replicates of each. We adjusted the intensity of different lights by controlling the number of the opened and closed LED bulbs, and outside light was blocked with a black cloth cover. The light intensities were measured with a GLZ-C quantometer (5 cm away from the inner wall of the outer chamber). In the morning (8:00–12:00), the light intensities of the yellow, green, white, red, and blue lights were controlled at 1100, 1100, 1300, 1600, and 1700 Lux, respectively. In the afternoon (12:00–18:00), the intensities of the yellow, green, white, red, and blue lights were controlled at 1600, 1600, 2300, 3000, and 2500 Lux, respectively. The night (18:00–8:00) was the dark treatment period, and the light intensities were all 0 Lux.

To guarantee the comparability of experiments, we chose rice plants of the same size (the fresh weight differences were between 0 and 2 g). The plants were then washed with deionized water, blow-dried and cultured in a PVC bucket with new culture solution (N concentration 90 mg L^{-1}, NH_4NO_3-N).

The rice seeds were selected and planted in soil on June 20, 2013, and three rice seedlings were planted in one PVC bucket with 6.0 L nutrient solution (this solution was replaced with new solution once a week) on July 10, 2013. The emissions of three GHGs were sampled from mature aging rice plants (116 days old, average fresh weight 290 g), and the samples were analyzed from October 10 to 16, 2013.

The mature aging rice plants were fixed across a foam board (4 cm in thickness), and every foam board was placed and sealed in the opening of the inner chamber with silica gel coating the board and junction gaps. In this way, we strictly separated and sealed the phyllosphere in the inner chamber and the roots in the outer chamber, with effectively no harm occurring on the rice plants.

GHG sampling and analysis

The inlet pipes and exhaust pipes of the inner and outer chambers were controlled by three-way valves, and airflow was regulated by a gas flow meter. The air in the inner and outer chambers was rapidly ventilated and uniformly mixed for 1.5 h with a gas pump (400 $L{\cdot}h^{-1}$) before every gas sampling time. The three ventilation

times were 8:00 to 9:30 (morning), 12:30 to 14:00 (afternoon), and 17:00 to 18:30 (evening). The self-designed monitoring box was kept sealed for 3.0 h after each ventilation, and the sealing times were 9:30 to 12:30 (morning), 14:00 to 17:00 (afternoon)m and 18:30 to 21:30 (evening). Gas samples were collected hourly (4 times) with a syringe (40 mL) to analyze the initial and hourly changes in N_2O, CO_2, and CH_4 concentrations during the 3-h sealed box periods. Air blank samples were simultaneously sampled. The experiment was repeated for 6 days. All gas samples were analyzed by gas chromatography (7890A GC system, Agilent Technologies, Santa Clara, CA, USA) within 12 h.[6]

Light quality and intensity settings

We further studied the effects of different light qualities and intensities on the three GHG emissions of mature aging rice plants in 2014.

In the weak light experiment, we set the same light qualities (8:00–18:00, 1600 Lux; 18:00–22:00, 0 Lux) in the selected lights (yellow, green, white, red, and blue lights) (repeated three times).

In the light intensity experiment, we set four light quality gradients from 8:00 to 18:00 (Dark, 0 Lux; Weak, 2000 Lux; Strong, 6000 Lux; Sunlight, average 28400 Lux, as CK), and the dark period was from 18:00 to 22:00 (0 Lux). This experiment was repeated three times.

The rice seeds were selected and planted in soil on May 20, 2014, and three rice seedlings were also planted in one PVC bucket with 6.0 L nutrient solution (this solution was replaced with new solution once a week) on June 10. The emissions of three GHGs were sampled from mature aging rice plants (110 days old, average fresh weight 315 g) and analyzed from September 10 to 16, 2014.

Emission rate calculation method

The emission rates of N_2O, CO_2 and CH_4 from different rice plant parts (phyllosphere and roots) were calculated per pot with Eqn (1).[19]

$$F = \rho \times V \times \frac{dc}{dt} \times \frac{273}{273+T} \quad (1)$$

F is the emission rate (μg pot^{-1} h^{-1} or mg pot^{-1} h^{-1});

ρ is the standard gas density (N_2O, 1.98 kg m^{-3}; CO_2, 1.96 kg m^{-3}; CH_4, 0.714 kg m^{-3});

V is the effective volume of the outer or inner chamber (m^3);

dc/dt is the rate of the gas concentration change that occurred in the sealing time interval (1 h) (ppb or ppm); and

T is the outer chamber air temperature (°C).

Statistical analysis

In all of the analyses, the light treatments were used as replicate potted rice plants (N = 3). The mean of the three samples was used as the result of one treatment. Negative values indicate absorption, and positive values indicate emission. Least significant difference (LSD) was used to assess pairwise differences (at 5% and 1% levels). All statistical analyses were conducted using the SPSS (Statistical Package for the Social Sciences) 13.0 software package (SPSS Inc. Chicago, IL, USA) and Microsoft Office 2003 (Microsoft Corporation, Redmond, WA, USA).

Results

N_2O emissions under different light controls

Net N_2O emissions from the phyllosphere and the roots of mature aging rice plants were observed at different times (morning, 8:00–12:00; afternoon, 13:00–17:00; night, 18:00–22:00) under different light control treatments (Table 1). Among these observations, the average N_2O emission rate of the phyllosphere in the weak LED light environment was 17.08 μg pot^{-1} h^{-1} (the average of the morning, afternoon and night values), accounting for 35.17% of the total N_2O emissions from the rice roots and the phyllosphere (an average of five treatments), and N_2O emission rates were significantly different between the five treatments. Based on our results, LED white light can simultaneously inhibit N_2O emissions from the rice roots and the phyllosphere significantly ($P < 0.01$) because N_2O emission rates were lower for the rice phyllosphere and the roots when irradiated with LED white light.

In the experiment comparing different light qualities, LED green light reduced the N_2O emission rate of the rice phyllosphere significantly ($P < 0.01$), but it increased the N_2O emission rate of the rice roots more than yellow LED light at the same intensity. In addition, the high intensity red and blue light treatments showed similar results to those of the green light. These results were significantly different from the LED white light treatment. LED white light can simultaneously inhibit the N_2O emissions of the roots and phyllosphere.

Table 1. The impact of different lights on N_2O emissions of the mature aging rice phyllosphere and root system (μg pot^{-1} h^{-1}). The data are presented as the mean value and standard error (SE). Mean values of the N_2O emission rates within the same column followed by different letters are significantly different among different lights ($p < 0.05$).

Monocolor Lights	N_2O emission rate (rice phyllosphere)			N_2O emission rate (rice roots)			Emission contribution of the phyllosphere (%)
	Morning	Afternoon	Night	Morning	Afternoon	Night	
Yellow	20.17±1.60 ABab	28.48±3.43 Aa	19.05±2.04 a	25.32±5.42 a	16.97±1.95 Cc	24.77±8.68 a	50.16
Green	8.53±1.00 Cd	13.25±0.42 Bb	15.59±4.55 a	23.63±10.67 a	39.81±6.53 ABCab	43.05±15.98 a	26.02
White	15.20±1.00 Bc	13.94±0.86 Bb	13.43±2.47 a	17.42±6.00 a	23.51±0.82 BCbc	20.48±6.86 a	41.14
Red	17.39±1.26 ABbc	16.98±1.49 Bb	14.83±1.11 a	40.03±9.48 a	54.76±5.85 Aa	32.27±10.80 a	28.48
Blue	22.18±1.26 Aa	17.12±1.07 Bb	20.02±1.29 a	56.32±20.14 a	47.35±8.35 ABa	36.53±4.18 a	30.07
Sunlight	23.12±4.27 Aa	23.23±3.10 Aa	22.47±3.45 a	11.22±2.52 a	17.63±3.29 Cc	16.33±3.70 a	60.37

The synchronized control trial showed that, under the same nitrogen concentration conditions (N = 90 mg·L^{-1}, NH_4NO_3-N), the average N_2O emission rate of the mature aging rice phyllosphere under outdoor natural sunlight was 22.94 μg pot^{-1} h^{-1} (the average of the morning, afternoon and night values), accounting for 60.37% of the total N_2O emissions from the rice roots and phyllosphere. Compared with the result for the weak LED white light, the N_2O emission rate under natural sunlight was significantly higher than the rate found in the rice phyllosphere, and it was significantly lower than the rate in roots ($P < 0.05$). Additionally, it increased the N_2O emission rate of the rice roots.

CO_2 emissions under different light controls

Net CO_2 emissions from the phyllosphere and the roots of mature aging rice plants are shown in Table 2. Among these values, the average CO_2 emission rate of the phyllosphere in the weak LED light environment was 35.3 mg pot^{-1} h^{-1}, accounting for 86.55% of the total CO_2 emissions from the rice roots and phyllosphere. As indicated by the results for yellow LED light irradiation, the average daily net CO_2 emission rate of the rice phyllosphere increased to 66.69 mg pot^{-1} h^{-1}. LED yellow light can increase rice leaf CO_2 emissions significantly ($P < 0.01$). During the same period, LED white, blue and red lights all inhibited the rice leaf CO_2 emissions to varying degrees, especially the blue light ($P < 0.05$). At different times (morning, afternoon, and evening) under natural sunlight, the rice phyllosphere showed net CO_2 emissions, which was significantly different from the net uptake of CO_2 observed during the tillering period and the flowering and fruiting period of the rice plants (results not shown). Under LED white, red, and blue lights, the net CO_2 emission rates of the roots were all lower than under sunlight (Table 2),

Table 2. The impact of different lights on CO_2 emissions of the mature aging rice phyllosphere and root system (mg pot^{-1} h^{-1}). The data are presented as the mean value and standard error (SE). Mean values of the CO_2 emission rates within the same column followed by different letters are significantly different among different lights ($p < 0.05$).

Monocolor Lights	CO_2 emission rate (rice phyllosphere)			CO_2 emission rate (rice roots)			Emission contribution of the phyllosphere (%)
	Morning	Afternoon	Night	Morning	Afternoon	Night	
Yellow	54.23± 4.58 Aa	93.79±7.73 Aa	52.06±12.65 a	5.07±0.68 a	14.35±3.62 Aa	6.74±0.35 a	88.91
Green	33.84± 1.92 Bb	38.12±2.82 ABb	35.26±4.47 a	5.11±0.33 a	6.46±0.44 Bb	4.72±1.99 a	86.86
White	28.44± 1.93 Bbc	20.21±2.88 BCc	32.20±5.86 a	4.57±0.08 a	5.51±0.61 Bb	4.12±1.35 a	84.45
Red	31.40± 3.97 Bb	23.45±3.26 BCc	39.08±6.38 a	3.10±0.34 a	4.32±0.32 Bb	3.38±0.85 a	89.17
Blue	20.15± 1.50 Bc	16.91±1.57 Cc	32.86±6.00 a	4.70±1.43 a	4.71±0.54 Bb	3.33±1.10 a	83.36
Sunlight	7.78±5.19 Cd	46.93±5.34 ABb	28.75±2.97 a	8.79±3.71 a	7.62±2.05 Bb	7.64±0.87 a	76.64

Table 3. The impact of different lights on CH_4 emissions of the mature aging rice phyllosphere and root system (mg pot^{-1} h^{-1}). The data are presented as the mean value and standard error (SE). Mean values of the CH_4 emission rates within the same column followed by different letters are significantly different among different lights ($p < 0.05$).

Monocolor Lights	CH_4 emission rate (rice phyllosphere)			CH_4 emission rate (rice roots)			Emission contribution of the phyllosphere (%)
	Morning	Afternoon	Night	Morning	Afternoon	Night	
Yellow	0.05±0.25 a	–0.13±0.80 a	–0.34±1.04 a	0.14±0.82 a	0.28±1.81 a	0.54±1.44 a	—
Green	0.30±0.78 a	–0.28±2.83 a	–0.16±0.27 a	0.63±1.25 a	–0.04±0.45 a	0.33±1.25 a	—
White	–0.10±0.27 a	–0.30±0.33 a	–0.26±0.87 a	–0.20±1.29 a	–0.16±1.66 a	–0.12±0.55 a	—
Red	0.15±0.13 a	0.14±0.57 a	–0.24±0.50 a	–0.20±0.77 a	0.14±0.82 a	–0.79±0.69 a	—
Blue	–0.04±0.13 a	–0.25±0.22 a	–0.03±0.85 a	0.29±1.35 a	–0.46±0.57 a	–0.58±0.55 a	—
Sunlight	–0.10±0.44 a	–0.05±0.51 a	0.56±0.78 a	0.37±0.96 a	–0.30±1.67 a	1.14±2.50 a	—

which indicated significant synchronous inhibition not only of the rice phyllosphere but also the root system CO_2 emissions.

Under natural sunlight, net CO_2 emissions from the rice phyllosphere accounted for 77.64% of the total emissions from the roots and the phyllosphere. In the mature aging period, the CO_2 emissions of the rice plants were mainly from the phyllosphere.

CH_4 emissions under different light controls

Under synchronous monitoring conditions, we did not observe net evaporation or absorption of CH_4 from the mature aging rice phyllosphere or root system (P>0.05); the absolute values of the monitoring data were very small (Table 3).

N_2O and CO_2 emissions under different light qualities

N_2O and CO_2 emissions of the mature aging rice under different light qualities with the same light intensity (8:00–17:00, 1700 Lux) were monitored in 2014. The results showed that, with the same light intensity, the rice phyllosphere N_2O emission rate under yellow light was significantly higher than the rates under green, white, red and blue lights ($P < 0.05$) (Fig. 2).

In the morning, afternoon and evening, the rice phyllosphere N_2O emission rates under white light were 62.89%, 45.44%, and 60.91%, respectively, of the rates at the same times under yellow light. N_2O emissions from the rice phyllosphere under green, red and blue lights were also lower, to varying degrees, than under the yellow light at the same time, but with no significant inhibition (P>0.05) (Fig. 2).

Synchronization tests showed that, in the morning, afternoon and evening under the same light intensity, the CO_2 emission rate from the rice phyllosphere under yellow light was significantly higher than the rates under green, white, red, and blue lights ($P < 0.05$) (Fig. 2).

When comparing the results in green, white, red, and blue lights in different light and dark control periods, the overall CO_2 emission rate results from the rice phyllosphere followed the order green > white > red > blue, and red and blue lights significantly inhibited the CO_2 emissions from the rice phyllosphere, especially blue light ($P < 0.05$) (Fig. 2). However, the rice root system CO_2 emission rates under different light qualities were not significantly different ($P > 0.05$).

N_2O and CO_2 emissions under different light intensities

In the rice mature aging period, the N_2O emissions from the rice leaf increased continually as light intensity increased in the range of 0 to 6000 Lux from morning to afternoon (Fig. 3). The highest N_2O emission rate occurred in the natural bright light treatment (average 28 400 Lux) ($P < 0.05$). In our results, the rice root system had a higher N_2O emission rate under indoor light (III, 6000 Lux) (Fig. 3). The N_2O emission rate from the rice roots was significantly lower under natural sunlight (IV) ($P < 0.05$), indicating that excessive daylight enhanced N_2O emissions from the rice phyllosphere while simultaneously inhibiting emissions from the rice root system.

In contrast to N_2O, the CO_2 emissions from the rice leaf decreased continually as light intensity increased in the range of 0 to 6000 Lux from morning to afternoon

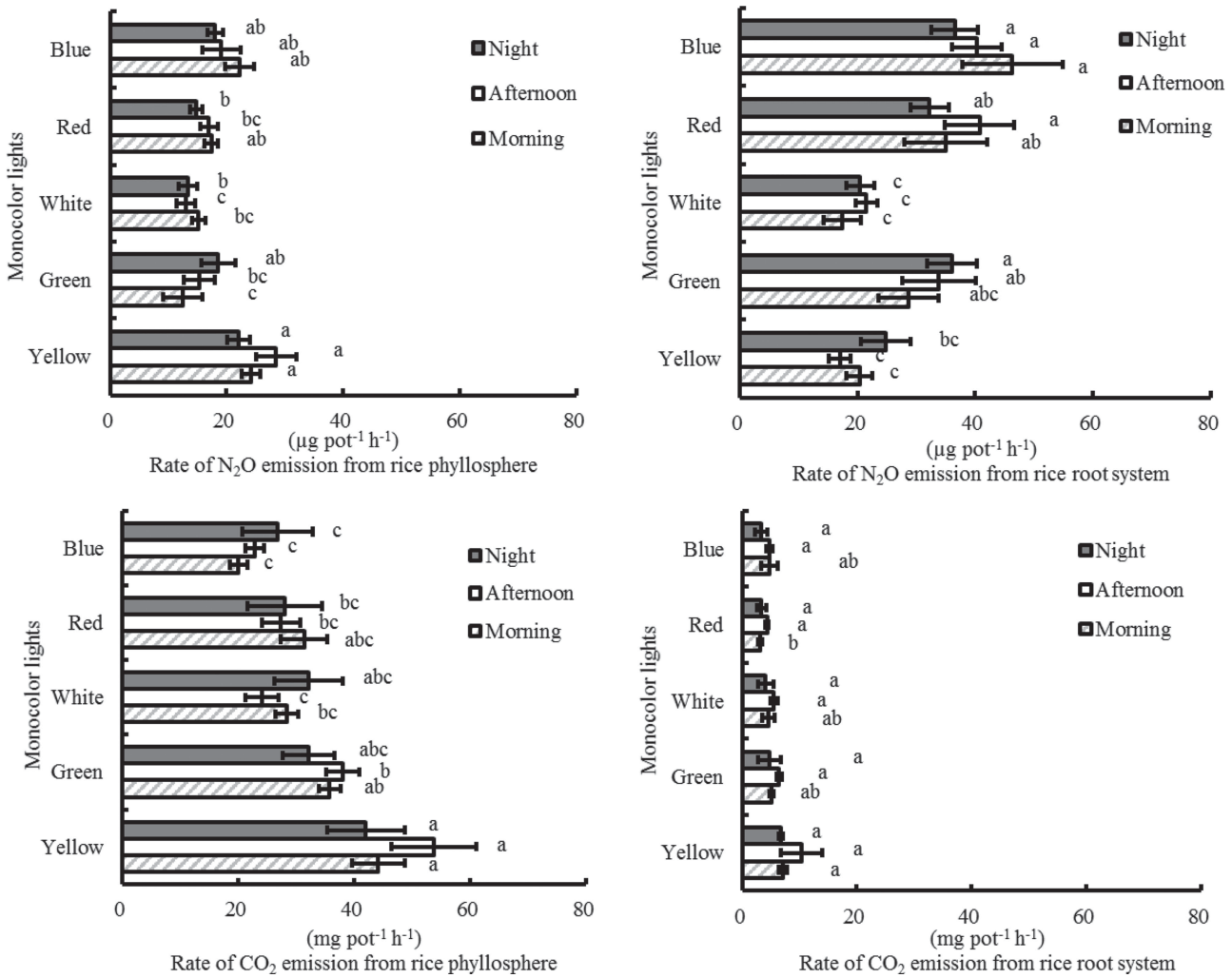

Figure 2. N_2O and CO_2 emission rates of the rice phyllosphere and root system in the mature aging period under different monocolor light.

($P < 0.05$) (Fig. 3). However, CO_2 emissions still occurred in the natural bright light treatment (average 28 400 Lux) (Fig. 3). CO_2 emissions from the root system also decreased as light intensity increased from 0 to 6000 Lux from morning to afternoon ($P < 0.05$) (Fig. 3). However, the CO_2 emission rates were still high (40.93 mg pot^{-1} h^{-1}, 13:00–18:00) in the natural bright light treatment (average 28 400 Lux) (Fig. 3).

Discussion

GHG emission contributions of the rice phyllosphere and the roots in the mature aging period

N_2O emissions from agricultural soils have attracted the attention of scientists and government dignitaries, but in recent years, some studies indicate that N_2O emissions can also be produced from the aerial parts of plants.[11–15,20–22] The problem is that N_2O is a product of chemical or biological denitrification, and it is difficult to strictly distinguish N_2O emissions from different sources, such as soil, air, or plant body. Thus, it is still difficult to assess the contribution of the plant phyllosphere to N_2O emissions, and rice is no exception. In this study, we designed an integrated GHG monitoring box (Fig. 1). This device can synchronously provide accurate quantitative monitoring of the N_2O emissions from the rice aerial leaf or the root parts by tightly separating the inside and the outside of the room with no harm to rice plant's normal growth. Our results confirmed that the mature rice phyllosphere in the senescence period has

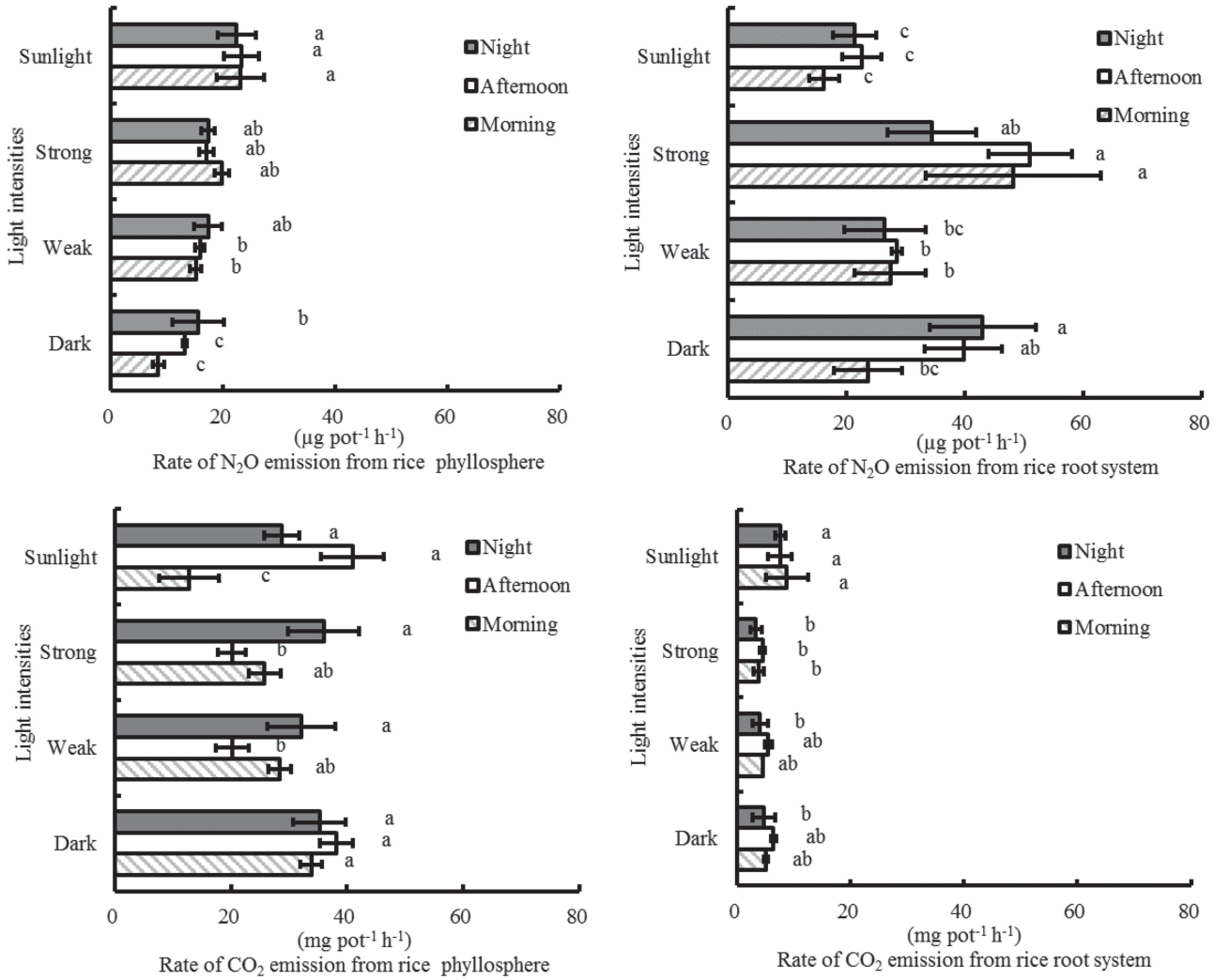

Figure 3. N_2O and CO_2 emission rates of the rice phyllosphere and root system in the mature aging period under different light intensities (Dark, 0 Lux; Weak, 2000 Lux; Strong, 6000 Lux; Sunlight, average 28 400 Lux, as CK).

a relatively large amount of N_2O-N emissions (60% of contribution), and the results also showed that rice phyllosphere N_2O-N emissions play an important role in agricultural nitrogen loss and serve as an important emission source of GHGs in the paddy field.

Kong *et al.* and Yu *et al.* found that the average CH_4 cumulative emissions of paddy fields was approximately 348.5 kg·hm^{-2} in the growing season under an intensive cultivation mode, and the contribution of the rice aerenchyma was 83% to 84%.[15,23] Keppler *et al.* estimated that the CH_4 source strength of living plants ranges from 62 to 236 Tg·yr^{-1}.[24] However, with synchronous, accurate quantitative monitoring of the rice aerial leaf and the root parts, we found no significant difference between the rice phyllosphere and the roots in net absorption or emission of CH_4, with no impact on the GHG emissions of the paddy ecosystem.

Compared with the N_2O gases (24.13%) and excluding CH_4, the additive contribution of CO_2 emissions from the mature aging rice roots and phyllosphere was approximately equal to 75.87%, which is the main source of GHGs in paddy ecosystems during this growth phase.

N_2O and CO_2 emissions under different light qualities, intensities and controls

Many studies indicate that, as light sources, red and blue light can significantly promote the growth and development of plants, and they can increase energy efficiency, photosynthetic rates and quality.[25] They

also increase the plant biomass per unit area and unit power.[26] The mature aging period is a period of strong respiration for plants, and our results show that, under the same conditions of weak LED light intensity (8:00–17:00, 1600 Lux), the rice phyllosphere and the roots have a high CO_2 emission rate under the yellow weak light condition, and there are also significantly high N_2O emissions from the rice leaf. These results indicate that weak yellow light increases the rice autotrophic respiration rate and promotes CO_2 emissions, and it also promotes the release of N_2O volatiles from the leaf. Plant respiratory metabolism provides rich sources of carbon and energy for photosynthetic nitrogen assimilation, but nitrogen assimilation is rapidly declining in mature aging rice. Carbon resources released by respiratory metabolism come in the form of CO_2 emissions rather than nitrogen re-assimilations. In addition, compared to yellow light, green, red, and blue lights not only inhibited CO_2 and N_2O emissions of the rice phyllosphere but also enhanced the N_2O emissions from the rice root-culture fluid system. Thus, the weak LED white light can synchronously inhibit N_2O and CO_2 emissions from the rice roots and the phyllosphere under the same light intensity, and similar results were obtained from two years of data. This shows that the composition of white light is more conducive to coordinating and balancing carbon and nitrogen metabolism, and it also inhibits N_2O and CO_2 emissions in mature aging rice plant roots and phyllosphere. NO_2^- is the precursor of N_2O in plants; plant nitrite reductase (NiR) can reduce endogenous NO_2^- to N_2O.[20] Thus, the inhibition of the formation of endogenous NO_2^- by NiR in the dark will affect N_2O emissions from the rice phyllosphere. Additionally, the dark treatment can affect transportation, accumulation and secretion of photosynthetic carbon substances in the rice roots and can affect nitrification and denitrification in the rhizosphere. These effects are the main reasons that the dark treatment inhibited both root and phyllosphere N_2O emissions, and they also explain why a modest light intensity increase within a certain range during the day (III light intensity profile, 6000 Lux) can effectively inhibit phyllosphere CO_2 emissions and enhance root and phyllosphere N_2O emissions of mature aging rice. It should be noted that, under natural conditions of high sunlight intensity, CO_2 emission rates of the rice roots and the phyllosphere and N_2O emission rates of the rice phyllosphere significantly increased, but the N_2O emission rate of the rice roots decreased significantly ($P < 0.05$). Our results in mature aging rice were not entirely consistent with the previous results examining moderate intensity and N_2O emissions in other growth stages.[12,13,22] We thought that this discrepancy may be due to the degeneration and aging of the conducting tissues in this period, which affects photosynthate transportation to the roots and inhibits related nitrification and denitrification processes.

Light regulation mechanisms for greenhouse gas emissions in mature aging rice

The wavelengths of visible light that are absorbed by plants are mainly in the 400–510 nm blue-violet band and the 610–720 nm red-orange band.[28] In our study, red and blue lights reduced CO_2 and N_2O emissions of the rice phyllosphere. This result was expected because red and blue are the major colors absorbed by plants. We found that, to some extent, we can control N_2O emissions from the rice roots or phyllosphere by adjusting the light intensity.

Because N_2O and CO_2 are the main sources of GHG emissions in mature aging rice, CO_2 and N_2O emissions are the key to reducing emissions in this period. LED green, red, and blue lights can inhibit rice leaf N_2O and CO_2 emissions, but they also increase the N_2O emissions of the rice root-culture fluid system. High intensity sunlight can inhibit N_2O emissions from the root-culture fluid system, which is followed by a CO_2 emissions increase, and improvement of the overall light intensity during the day can enhance the effect of the rice leaf volatile N_2O. However, we observed that N_2O and CO_2 emission rates both decreased significantly in the rice roots and the phyllosphere only under weak LED white light. This result indicates that, in addition to intensity and quality, the coordinated effects of intensity and quality affect rice volatilization of N_2O and CO_2. As this study shows, by adjusting the composition of visible light by using a modest technical measure to increase red and blue light proportions, and by simultaneously controlling light intensities, light qualities and intensities can be made to beneficially inhibit N_2O and CO_2 emissions of the rice roots and phyllosphere.

Light control may be the key to low-carbon technology for GHG emission reductions in the mature paddy ecosystem. These findings could be useful wherever rice is being cultivated under controlled

greenhouse conditions. However, it remains to be seen how these measures or technologies could be applied under practical field conditions because controlling light under field conditions is far from practical in most developing countries. We need to carry out a series of continuous in-depth studies in the future. We also need to analyze the extent of GHG mitigation that can be achieved to determine the optimum ratio of economic investment to cost and the environmental benefit in practical field conditions through environmental economics.

Acknowledgments

This study was supported by the Project of the National Natural Science Foundation of China (31160412, 41361056, and 41201298), the Project of the Natural Science Foundation of Yunnan Province (2001FZ183), and the Project of the Introducing Talents of Kunming University (YJL12012). We would like to convey our deepest gratitude to the anonymous reviewers for your valuable comments which supported us to develop the manuscript. We are grateful to NPG Language Editing and Wiley Editing Services for their English language editing services on the manuscript.

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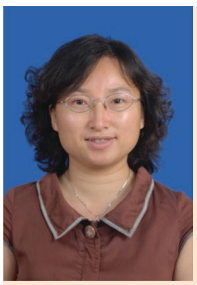

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