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Response of GHG emissions to interactions of temperature and drying in the karst wetland of the Yunnan-Guizhou Plateau

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Hydrothermal fluctuation is the major driving factor affecting greenhouse gas (GHG) emissions in wetlands, but how wetland drying regulates the temperature dependence of GHG emissions remains uncertain. An experimental incubation was carried out to study the interaction effects of temperature (5, 10, 15, 20°C) and moisture (40%, 60%, 100% WHC) on soil GHG emissions in a karst wetland. The results showed that: 1) the cumulative CO_2 and N_2O emissions and global warming potential (GWP) increased with increasing temperature but decreased with soil drying. 2) There was a decreasing contribution of CO_2 and an increasing contribution of N_2O to GWP with increasing temperature and moisture. 3) Soil CO_2 and N_2O emissions and GWP were positively related to urease activity and negatively related to pH, soil organic matter and catalase. Soil CH_4 emissions were positively related to soil microbial biomass C and N. The hydrothermal changes, soil properties and their interaction explained 26.86%, 9.46% and 49.61% of the variation in GWP. Our results indicate that hydrothermal fluctuation has a significant effect on total GHG emissions by regulating soil properties.

KEYWORDS

hydrothermal fluctuation, CH_4, N_2O, global warming potential, soil incubation

1 Introduction

Wetlands cover 5%–8% of the global landscape (Fennessy, 2014) but account for approximately 15% of the terrestrial organic carbon stock (Han et al., 2013), which plays a critical role in regulating global carbon cycling and climatic change (Xiong et al., 2015; Salimi et al., 2021). Meanwhile, wetlands are a large source of CH_4 and N_2O (Sovik et al., 2006; Kayranli et al., 2010), in which global warming potential (GWP) is 28 and 298 times higher, respectively, than CO_2 on a 100-year time scale (Wang et al., 2021). Although many factors have been determined to affect wetland greenhouse gas (GHG) emissions, the soil temperature and water content are confirmed to be the two major factors influencing GHG emissions (Toczydlowski et al., 2020; Docherty and Thomas, 2021).

Climate change can alter wetland ecosystem biogeochemistry and affect gas emissions by increasing temperature and changing hydrological patterns (Salimi et al., 2021). Therefore, quantifying the response of GHG emissions to soil temperature and water content changes is critical to predicting the potential effect of wetlands on global warming.

Many studies have reported that there is an increasing trend of GHG efflux as the temperature and moisture increase in a certain range (Yang et al., 2013; Yvon-Durocher et al., 2014; Toczydlowski et al., 2020; Zhao et al., 2020). For instance, CO_2 and CH_4 emissions could increase approximately 3 times for every 10°C increase in temperature (McKenzie et al., 1998); elevating temperature significantly promotes soil CH_4 and N_2O emissions from wetlands (Liu et al., 2017; Toczydlowski et al., 2020). Higher temperatures can promote soil organic matter decomposition (Yang et al., 2013), microbial biomasses (Baldock et al., 2012), C cycle-related enzyme activities (Bell et al., 2010), and chemical reaction rates (Reichstein et al., 2013), thus enhancing greenhouse gas emissions. The moisture effect on wetland GHG emissions is dependent on the aerobic and anaerobic situations (Salimi et al., 2021). CO_2 emissions are often higher in unsaturated soils, while flooding causes a reduction in CO_2 and an increase in CH_4 emissions in wetlands (Yang et al., 2013; Zhao et al., 2020). Wetland moisture is crucial to the substrate supply for soil microorganisms and oxygen diffusivity (Salimi et al., 2021). On the one hand, unsaturated moisture is beneficial for forming an aerobic environment and providing more organic substrates for aerobic microorganisms, which in turn facilitates soil C and N mineralization and CH_4 oxidation (Yang et al., 2013; Henneberg et al., 2016; Zhang T. et al., 2020). On the other hand, excessive moisture prevents the proliferation of O_2 and further limits aerobic microbial activity, resulting in a decrease in CO_2 emissions (Martikainen et al., 1993; Yang et al., 2013). Furthermore, excessive moisture promotes anaerobic microsites and therefore promotes CH_4 emissions (Kang et al., 2012) and N_2O efflux through denitrification (Dobbie and Smith, 2001). However, some studies have reported that higher temperatures have a small effect on CO_2 emissions (Liu et al., 2017) or reduce CH_4 emissions when wetlands are constrained by the soil water content (Houweling et al., 2000; Kang et al., 2012), while increasing moisture decreases N_2O emissions (Zhang, et al., 2020). These different results reveal that the response of wetland GHG emissions to soil temperature and water content changes remains inconclusive.

Wetlands are normally distributed in ecotones between aquatic and terrestrial ecosystems, leading to inevitable hydrothermal fluctuations in temperature and moisture (Salimi et al., 2021). Although many field studies have been performed on the factors affecting soil GHG flux rates in wetlands globally, it is difficult to determine a single parameter because other factors usually covary or interact (Zhao et al., 2020). Laboratory incubation has proven to be a

feasible approach for overcoming confounding covariations. Many studies have researched the potential mechanisms of wetland GHG emissions under various temperature and moisture conditions (Liu et al., 2017; Zhao et al., 2020), whereas only a few studies have focused on the interactions of temperature and moisture (Gao et al., 2011; Toczydlowski et al., 2020). Moreover, there are large seasonal variations in hydrological cycling due to human impacts such as artificial drainage (Chen et al., 2018) and climate change, such as temperature increases and precipitation reductions (Wu et al., 2017; Salimi et al., 2021), which in turn cause long-term drier rather than wetter conditions in many wetlands (Zhao et al., 2020). Therefore, it is critical to elucidating the responses of GHG emissions to unsaturated moisture conditions combined with temperature.

Guizhou Province, as the center of karst landform in southwest China (Wang L. et al., 2018), is one of the largest and continuous typical karst region in China (Liu et al., 2022). Its exposed karst land has caused soil degradation, soil erosion and a sharp decline in soil productivity. It also aggravates the problems of drought and flood. As one of the important sources of GHG emissions in plateau regions, wetland ecosystems are extremely vulnerable and particularly sensitive to global warming and related changes in temperature and precipitation (Yang et al., 2014; Liu et al., 2022). Study has shown that the coverage rate of karst wetland ecosystem is increasing at an average rate of about 5% per decade (Fan et al., 2015). Therefore, the study on the impact of temperature and moisture changes on GHG emissions in karst wetland ecosystems has important guiding significance for future global climate change.

Therefore, we conducted an incubation experiment, made up of four temperature gradients and three moisture gradients, in the karst wetland of the Yunnan-Guizhou Plateau. The objectives of the present study were 1) to determine the interactions of temperature and soil drying on CO_2, CH_4 and N_2O emissions, 2) to compare the contribution of three greenhouse gases to global warming potential (GWP), and 3) to explore the relationship between soil factors and GHG emissions.

2 Methods

2.1 Experimental design

Incubation samples were collected at a depth of 0–10 cm from calcareous soil located in Huaxi National Urban Wetland Park (26°29'~26°36'N, 106°27'~106°52'E) in Guiyang City, which is in a typical karst wetland on the Yunnan-Guizhou Plateau. Each sample was freeze-dried and passed through a 2 mm sieve. We conducted a 3 × 4 factorial design with two factors: a temperature gradient of 5 (T_5), 10 (T_{10}), 15 (T_{15}), and 20°C (T_{20}) and a moisture gradient of 40% (W_{40}), 60% (W_{60}), and 100% (W_{100}) water-holding capacity (WHC). There were

12 treatment combinations with three replicates in each treatment.

Before incubation, 100 g freeze-dried soil was put into a 250 ml plastic jar, and then deionized moisture was added to adjust the required soil moisture content. Then, the jars were placed in four constant temperature incubators (LRH-100CA, Shanghai Yiheng Co. Ltd, China) at a gradient of 5, 10, 15 and 20°C, respectively. The jars were covered with perforated plastic film to facilitate gas flow. During the cultivation period, a weighing method was used to maintain constant moisture by adding deionized water every 5 days.

2.2 Greenhouse gas measurement

The jars were flushed with fresh air for 20 min to clear the gas accumulated in the culture flask before taking the gas sample and were then sealed the jars *via* a cap with a three-way valve. The gas samples were collected at 0 and 30 min using a 10 ml syringe after 1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 25 and 30 days of incubation.

Gas samples were using gas chromatography (GC-2014, Shimadzu, Japan). The contents of CH_4 and CO_2 were determined by the front detector FID (hydrogen flame ion detector) at 200°C. N_2O concentration was determined by an ECD (electron capture detector) at 300°C and 99.99% high purity nitrogen as the carrier gas. The GHG flux rate was calculated following (Junna et al., 2014).

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

where F is the instantaneous rate of greenhouse gas, ρ is the gas density (kg m^{-3}), $\frac{dc}{dt}$ is the increase in gas concentration in the culture flask per unit time, V is the gas volume of jars headspace (m^3), m is the mass of soil (kg), and T is the culture temperature. The cumulative greenhouse gas emission was determined by the sum of the productions of the average rate and the time between sampling dates (Zhang et al., 2015).

The global warming potential (GWP, mg kg^{-1}, CO_2 equivalent) was calculated following the formulae of (Wang et al., 2021).

$$GWP = CE_{CO_2} + CE_{CH_4} \times 28 + CE_{N_2O} \times 298 \qquad (2)$$

2.3 Data analysis and statistics

Two-way ANOVA was used to test the effects of temperature, moisture and their interactions on GHG emissions and GWP. The LSD test was used to test the difference among all treatments. Pearson correlation was used to analyse the correlation between greenhouse gas emissions and soil factors. Statistical analysis was conducted by using IBM SPSS Statistics 26 and Origin Pro 2021. Variance

decomposition analysis was implemented by the varpart function in the "Vegan" package of RStudio. All analyses were defined as significant at the 0.05 level.
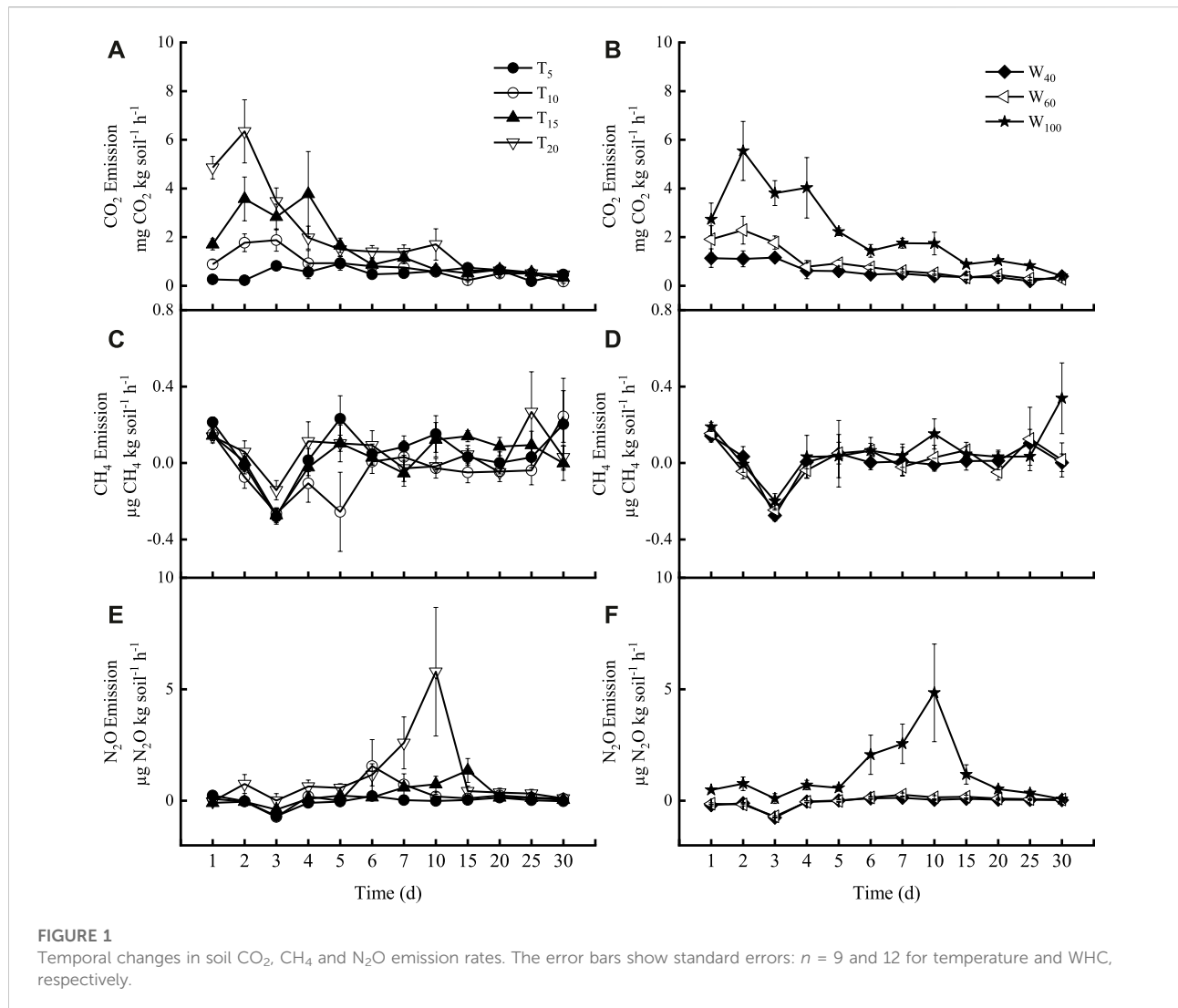
3 Results

3.1 Temporal changes in GHG emission rates

The CO_2, CH_4, and N_2O emission rates of all treatments showed similar variations with incubation time (Figure 1). The CO_2 emission rate reached a maximum before the third day and then decreased gradually to stable in both the temperature and moisture treatments (Figures 1A,B). The CH_4 emission rate was lowest on the third day and then increased to stable in both the temperature and moisture treatments (Figures 1C,D). The N_2O emission rate of each treatment showed small fluctuations during the whole incubation period, except for a peak value in T_{20} and W_{100} on the 10th day (Figures 1E,F).

3.2 Cumulative GHG emissions and GWP

Soil CO_2 emissions increased with increasing temperature (Figure 2A), increasing by 5.6% (T_{10}), 76% (T_{15}, $p < 0.05$), and 133% (T_{20}, $p < 0.05$) compared to T_5 (Figure 2A and Table 1). The soil N_2O emissions of T_{15} and T_{20} showed significant increases compared to T_5 (Figure 2E and Table 1). Soil CH_4 emissions were not significantly affected by temperature (Figure 2C, $p > 0.05$). The soil CO_2 emissions increased by 31% (W_{60}) and 209% (W_{100}, $p < 0.05$) compared to W_{40}; soil N_2O emissions showed significant increases in W_{100} compared to W_{40} (Figures 2B,F, $p < 0.05$). The cumulative CH_4 emissions increased with increasing moisture (Figure 2D); however, there were no significant differences between treatments due to the complicated response under different temperature levels (Table 1 and Figure 3B).

The GWP increased by 14% (T_{10}), 95% (T_{15}, $p < 0.05$), and 185% (T_{20}, $p < 0.05$) compared to T_5 (Table 1). The GWP of W_{100} was significantly increased compared to that of W_{40} (Table 1, $p < 0.05$). The contribution of CO_2 to GWP was more than 84.93% and decreased with temperature and moisture increases, but the contribution of N_2O to GWP increased with temperature and moisture increases (Table 2). Temperature, moisture and their interactions had significant effects on CO_2/GWP and N_2O/GWP (Table 2, $p < 0.01$). There were significant effects of temperature and moisture interactions on CO_2 and N_2O emissions and GWP (Table 1). The CO_2 and N_2O emissions and GWP of W_{100} were significantly higher than those of W_{40} and W_{60} among the different temperature gradients, and there were significant differences in CO_2 emissions and GWP between W_{40} and W_{60} under the T_{10} treatment ($p < 0.05$, Figures 3A,D).

FIGURE 1
Temporal changes in soil CO_2, CH_4 and N_2O emission rates. The error bars show standard errors: n = 9 and 12 for temperature and WHC, respectively.

3.3 Factors affecting GHG emissions

Temperature had significant effects on SOM, but there was no interaction between temperature and moisture. Soil MBC, MBN and NH_4^+-N significantly decreased with increasing soil drying and temperature; in contrast, soil sucrase increased with increasing temperature and drying (Table 3, $p < 0.05$). Soil catalase and urease increased as the temperature (Table 3, $p < 0.05$) increased from 40% WHC to 60% WHC and then decreased down from 100% WHC.

Pearson correlation analysis showed that the cumulative CO_2 and N_2O emissions and GWP were positively related to soil moisture, temperature, and urease activity and negatively related to pH, SOM and catalase ($p < 0.05$, Figure 4A). The cumulative CH_4 emissions were positively related to MBC and MBN (Figure 4A, $p < 0.05$). Variance decomposition analysis found that hydrothermal, soil properties and their interaction explained

26.86%, 9.46% and 49.61% of the variation in GWP, respectively (Figure 4B).

4 Discussion

4.1 Effects of soil temperature on GHG emissions

Higher temperatures significantly promoted CO_2 emissions in this study (Table 1), which is in line with many previous studies (Schaufler et al., 2010; Zhang et al., 2020; Toczydlowski et al., 2020). Gao et al. (2011) reported that the soil CO_2 emission rate increased by 2.4–3.7 times in swamps and peat wetlands from 5 to 35°C. Increasing temperature can promote soil microbial activity and decomposition of soil organic matter by improving microbial substrate availability (Silvola et al., 1996;

FIGURE 2
Temporal changes in soil cumulative CO_2, CH_4 and N_2O emissions. The error bars show standard errors: $n = 9$ and 12 for temperature and WHC, respectively.
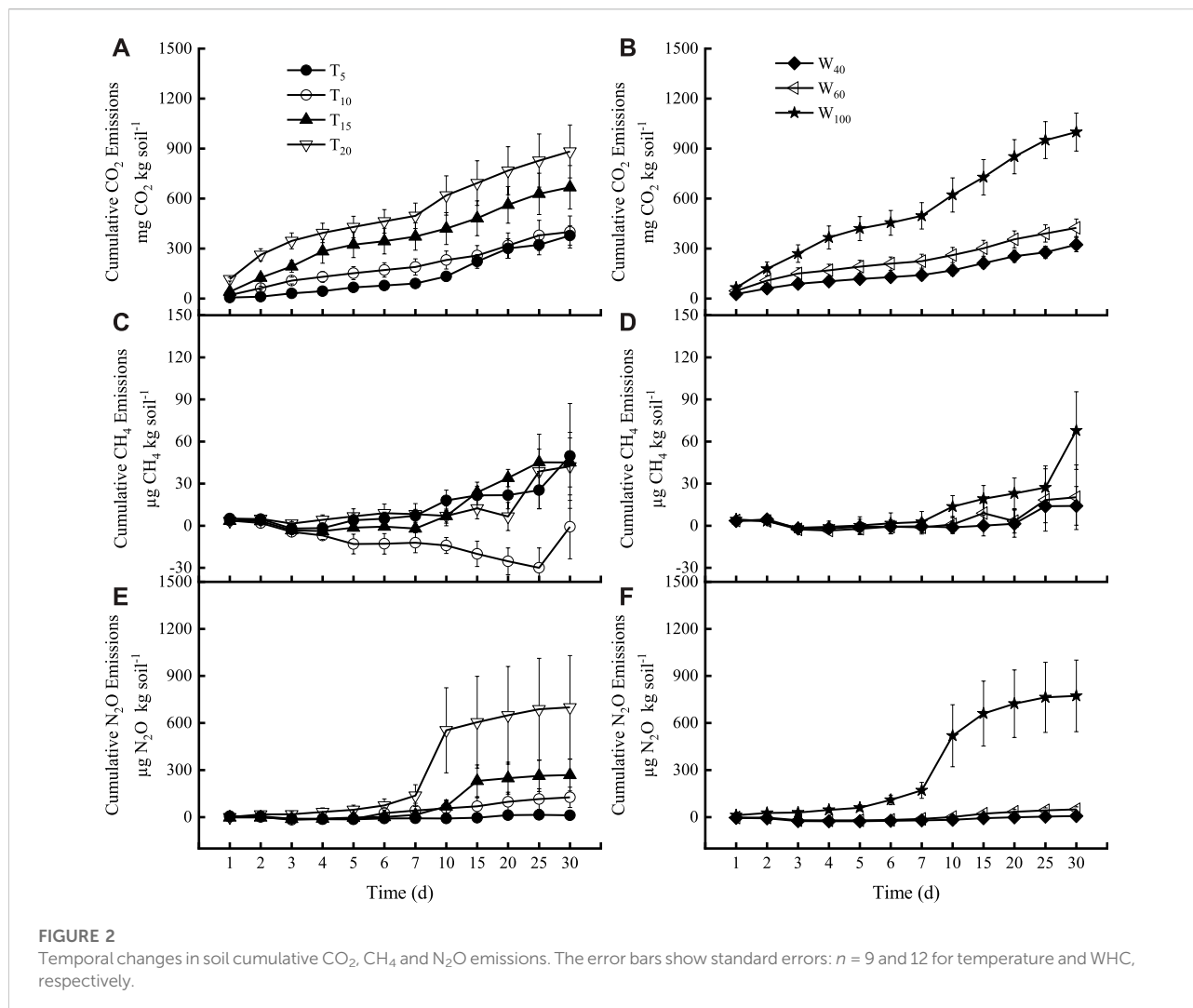
Inglett et al., 2012), thus increasing CO_2 emissions and reducing soil SOC content (Na et al., 2011). We found that SOM, MBC and MBN significantly decreased with increasing temperature and were negatively related to CO_2 emissions (Figure 4A). Previous studies also found that increasing temperature resulted in decreases in SOC (Kirschbaum, 2000; He et al., 2020), MBC and MBN (Rinnan et al., 2009; Fu et al., 2012).

Elevating temperature often leads to a higher methane efflux under both aerobic and anaerobic conditions (Inglett et al., 2012; Vilakazi et al., 2021). For example, Macdonald et al. (1998) indicated that the CH_4 emission rate showed an exponential increase between 5 and 30°C. However, we found that there were no differences among the four temperature gradients due to the complicated responses under different moisture levels (Figure 3B). Temperature alters CH_4 production by affecting soil organic matter, C availability, redox processes, and bacterial community changes such as methanogens abundance, composition and activity (Morrissey et al., 2014; Li et al.,

2020). Li et al. (2020) indicated that high MBC and MBN contents are a potential mechanism leading to high CH_4 emissions. Our study showed that CH_4 emissions were positively related to MBC and MBN (Figure 4A), indicating that temperature affects CH_4 emissions by regulating microbial biomass C and N.

In our study, increasing temperature significantly promoted N_2O emissions, with a maximum in the T_{20} treatment (Table 1), which was consistent with previous studies conducted in Tibetan (Liu et al., 2017) and European wetland soils (Schaufler et al., 2010). Cui et al. (2018) found that elevating temperature increased the N_2O flux rate by 147% in a northern peat wetland. Elevating temperature could stimulate the soil nitrogen mineralization rate, which in turn increases the availability of mineral nitrogen and provides a nutrient supply for nitrification and denitrification to produce N_2O (Morse and Bernhardt, 2013). We found that elevating temperature significantly reduced soil NH_4^+-N and increased NO_3^--N

TABLE 1 Cumulative greenhouse gas emissions (means $\pm$ se).

Treatments	Variables			
	CO_2 (mg kg soil^{-1})	CH_4 (µg kg soil^{-1})	N_2O (µg kg soil^{-1})	GWP (mgCO$_{2(eq)}$ kg^{-1})
WHC				
40%	323.51 ± 42.29b	14.15 ± 13.81a	7.31 ± 11.15b	326.08 ± 45.04b
60%	424.52 ± 52.65b	20.31 ± 23.00a	49.56 ± 15.77b	439.86 ± 55.73b
100%	998.86 ± 113.92a	67.82 ± 27.7a	772.85 ± 227.87a	1,231.07 ± 175.73a
Temperature(T)				
5°C	378.60 ± 58.00c	49.74 ± 37.35a	11.54 ± 19.36c	383.44 ± 63.52c
10°C	399.68 ± 95.91c	-0.78 ± 22.76a	126.39 ± 64.79bc	437.32 ± 113.89c
15°C	668.07 ± 130.56b	45.11 ± 17.44a	268.02 ± 101.13b	749.20 ± 160.64b
20°C	882.84 ± 158.78a	42.31 ± 24.30a	700.35 ± 329.76a	1,092.73 ± 253.11a
ANOVA				
WHC	<0.01	0.20	<0.01	<0.01
T	<0.01	0.50	<0.01	<0.01
WHC×T	0.06	0.46	<0.01	<0.01

Different letters in each treatment indicate significant differences in LSD, tests. The number (n) of replicates for each mean varies with the treatments: n = 9 and 12 for temperature and WHC, respectively.

content (Table 3). Even with an extremely low NH_4^+-N content, the ammonia-oxidizing archaeal community could still use NH_4^+-N to produce NO_3^--N (Martens-Habbena et al., 2009). Although soil was not incubated at higher temperatures in the present study, a previous study reported that the N_2O emissions were higher than those at 20 °C when the temperature increased to 25 and 34°C, and high temperature promoted the expression of denitrifying genes (Wang et al., 2018).

4.2 Effects of soil moisture on GHG emissions

We found that the soil CO_2 emissions at 100% WHC were 3.1 times higher than those at 40% WHC (Table 1). This result is similar to (Maucieri et al., 2017), who observed that soil CO_2 emissions increased by 2.7 times from 25% to 100% WHC in Australia. Soil moisture usually determines the decomposition rate of soil organic matter in wetlands (Burkett and Kusler, 2000). Generally, soil CO_2 emissions are positively correlated with moisture under unsaturated moisture conditions (Silvola et al., 1996; Blodau et al., 2004). Oxygen diffusion to deep soil can increase organic matter mineralization, and CO_2 production from aerobic respiration is more effective than anaerobic respiration, which in turn accelerates CO_2 transport in unsaturated soil (Yang et al., 2013). In addition, soil microbes are more active when there is moisture below the soil surface, and these microbes utilize the active organic carbon matrix, which directly causes higher CO_2 emissions (Chimner and Cooper, 2003). However, some studies found that moisture was negatively related to CO_2 emissions under seasonal flooded conditions

(Chen et al., 2013; Zhao et al., 2020). The excessive increase in moisture can mitigate the diffusion and availability of O_2 in soil, thus reducing CO_2 emissions by limiting the activity of aerobic microbes and the decomposition of SOC (Jimenez et al., 2012; Yang et al., 2014; Khalid et al., 2019).

Soil moisture is a major factor in regulating CH_4 oxidation and emission (Khalid et al., 2019). We found that higher moisture promoted CH_4 emissions, which were highest at 100% WHC (Table 1). Higher moisture can reduce the oxygen concentration, which is beneficial to the anaerobic decomposition of methanogens, thus promoting CH_4 production (McInerney and Helton, 2016). Instead, the CH_4 emission rate may be reduced under low moisture conditions by enhancing CH_4 oxidation (Maucieri et al., 2017). Moreover, soil CH_4 emissions were positively correlated with MBC and MBN in this study (Figure 4A). Soil organic carbon is the carbon source and energy for generating CH_4, in which microbial biomass carbon can provide a substrate for methanogens (Li et al., 2020). Many previous studies also reported that soil MBC had a highly positive correlation with CH_4 emissions (Rasilo et al., 2017; Zhou et al., 2019). In addition, methanotrophic bacteria have a certain demand for NH_4^+-N (Bodelier and Laanbroek, 2004), which can increase the activity of methanogens and reduce the activity of methane bacteria (Bodelier et al., 2012), thereby increasing methane emissions. Although moisture had no significant effect on NH_4^+-N content in the present study, there was a significant interaction of moisture and temperature on NH_4^+-N content (Table 1).

Our study found that increasing soil moisture promoted N_2O emissions, with the highest emissions in the 100% WHC treatment (Figure 2F). A previous study also found that the largest N_2O emissions occur at 80% and 100% water-filled porosity spaces (Ciarlo et al., 2007). Soil moisture is often

FIGURE 3
Interactions of temperature and moisture treatment on soil cumulative CO_2, CH_4 and N_2O emissions at the end of culture. The capital letters are the differences between the same temperature and different moisture treatments, and the lowercase letters are the differences between the same moisture and different temperature treatments. The error bars show standard errors: $n = 3$.

TABLE 2 The contributions of CO_2, CH_4 and N_2O emissions to GWP.

Treatments	CO_2/GWP (%)	CH_4/GWP (%)	N_2O/GWP (%)
WHC			
40%	100.88 ± 1.37a	0.15 ± 0.14a	−1.03 ± 1.36b
60%	97.27 ± 1.15a	0.08 ± 0.19a	2.65 ± 1.16b
100%	84.93 ± 2.79b	0.22 ± 0.11a	14.85 ± 2.84a
Temperature(T)			
5°C	100.43 ± 1.34a	0.25 ± 0.26a	−0.69 ± 1.30b
10°C	96.66 ± 2.97ab	−0.01 ± 0.15a	3.35 ± 2.99ab
15°C	91.94 ± 1.66b	0.22 ± 0.12a	7.84 ± 1.69a
20°C	88.41 ± 4.43b	0.14 ± 0.11a	11.45 ± 4.45a
ANOVA			
WHC	$p < 0.01$	0.84	$p < 0.01$
T	$p < 0.01$	0.75	$p < 0.01$
WHC×T	$p < 0.01$	0.71	$p < 0.01$

TABLE 3 Soil properties after 30 days of incubation.

Treatments	pH	SOM/(g kg^{-1})	TN/(g kg^{-1})	TP/(g kg^{-1})	MBC/ (mg kg^{-1})	MBN/ (mg kg^{-1})	NH$_4^+$-N/(mg kg^{-1})	NO$_3^-$-N/(mg kg^{-1})	Catalase/ (ml g^{-1} h^{-1})	Urease/ (mg g^{-1})	Sucrase/ (mg g^{-1})
WHC											
40%	8.08 ± 0.01a	47.85 ± 0.34a	2.48 ± 0.03a	0.46 ± 0.07a	89.82 ± 17.98a	22.96 ± 5.11 b	27.68 ± 8.128a	51.17 ± 7.80a	6.39 ± 0.11a	0.35 ± 0.04a	8.16 ± 1.43a
60%	8.05 ± 0.02a	47.64 ± 0.15 ab	2.39 ± 0.03a	0.32 ± 0.04a	128.38 ± 16.83a	49.33 ± 4.83 ab	29.51 ± 13.14a	47.33 ± 8.93a	6.57 ± 0.26a	0.43 ± 0.06a	3.61 ± 0.65b
100%	8.05 ± 0.01a	47.05 ± 0.29b	2.39 ± 0.03a	0.52 ± 0.09a	205.90 ± 66.31a	79.22 ± 17.09a	28.02 ± 12.69a	62.42 ± 8.51a	4.90 ± 0.20b	0.38 ± 0.05a	1.22 ± 0.40b
Temperature											
5°C	8.12 ± 0.01a	48.17 ± 0.19a	2.39 ± 0.03ab	0.59 ± 0.08a	303.36 ± 71.37a	85.99 ± 21.80a	92.68 ± 5.30a	2.15 ± 0.43c	5.49 ± 0.20a	0.13 ± 0.00c	0.84 ± 0.26b
10°C	8.07 ± 0.01b	47.76 ± 0.23ab	2.36 ± 0.03b	0.34 ± 0.03b	98.95 ± 15.88b	39.32 ± 6.25b	11.25 ± 3.44b	52.86 ± 5.46b	5.91 ± 0.50a	0.43 ± 0.01b	4.24 ± 0.87ab
15°C	8.04 ± 0.01c	47.24 ± 0.41bc	2.48 ± 0.04a	0.38 ± 0.08 ab	112.24 ± 17.10 b	44.79 ± 8.95 b	5.46 ± 0.80 b	53.57 ± 3.84 b	6.02 ± 0.21a	0.42 ± 0.01 b	5.00 ± 1.31a
20°C	8.01 ± 0.01d	46.87 ± 0.29c	2.46 ± 0.04ab	0.42 ± 0.11ab	50.91 ± 8.14 b	31.91 ± 8.67b	4.22 ± 0.34b	69.55 ± 4.10a	6.40 ± 0.34a	0.57 ± 0.03a	7.25 ± 1.94a
ANOVA	P value										
WHC	<0.001	0.087	0.016	<0.001	<0.001	<0.001	0.251	0.035	<0.001	0.001	<0.001
T	<0.001	0.023	0.012	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001
WHC × T	<0.001	0.846	0.005	<0.001	<0.001	<0.001	<0.001	0.008	<0.001	0.039	<0.001

The error bars show standard errors: n = 9 and 12 for temperature and WHC, respectively. Different letters in each treatment indicate significant differences.
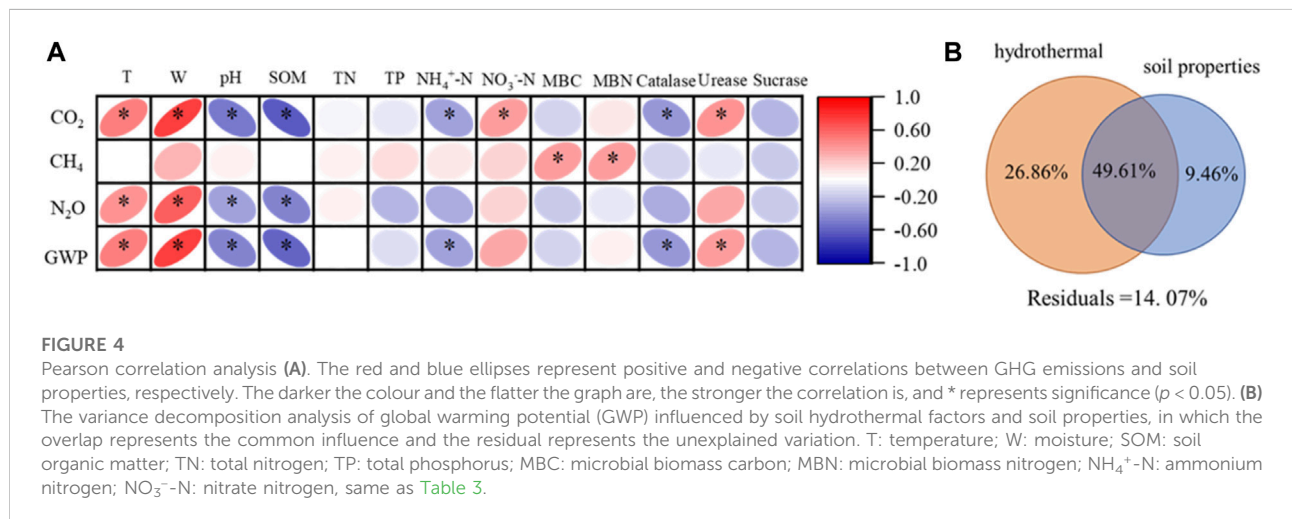

FIGURE 4
Pearson correlation analysis (A). The red and blue ellipses represent positive and negative correlations between GHG emissions and soil properties, respectively. The darker the colour and the flatter the graph are, the stronger the correlation is, and * represents significance (p < 0.05). (B) The variance decomposition analysis of global warming potential (GWP) influenced by soil hydrothermal factors and soil properties, in which the overlap represents the common influence and the residual represents the unexplained variation. T: temperature; W: moisture; SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; NH$_4^+$-N: ammonium nitrogen; NO$_3^-$-N: nitrate nitrogen, same as Table 3.

positively correlated with N_2O emissions (Schaufler et al., 2010), including linear (Dobbie and Smith, 2001), quadratic (Ciarlo et al., 2007) or exponential relationships (Dobbie and Smith, 2003), while a few studies have shown no obvious relationship between N_2O emissions and moisture change (Krauss and Whitbeck, 2012). N_2O production is the result of nitrification and denitrification with the participation of soil microorganisms (Braker and Conrad, 2011). Higher moisture can increase the soil soluble carbon content for microbes to provide sufficient C and N sources and improve the microbial nitrogen conversion rate, thus increasing N_2O emissions (Wu et al., 2022). In addition, wetland N_2O emissions are affected by NH_4^+-N content to a certain extent, which could be produced by nitrification of NH_4^+-N (Cui et al., 2016).

4.3 Temperature interaction with moisture on GWP

We found that soil CO_2 and N_2O emissions were significantly affected by temperature and moisture interactions in this study (Table 1), which was consistent with the results of black ash wetlands in this study (Toczydlowski et al., 2020). We found that soil CO_2 and N_2O emissions under high moisture (W_{100}) were significantly higher than those under low moisture (W_{40} and W_{60}) in all temperature treatments (Table 1; Figures 3A,C). (Rey et al., 2010) indicated that moisture had a greater effect on soil CO_2 emissions than temperature under low moisture conditions (40% and 60% WHC), while temperature had a greater effect on CO_2 emissions under higher moisture conditions (100% WHC). However, the temperature and moisture interaction had no significant impact on CH_4 emissions in the present study (Table 1), which was inconsistent with other studies. For instance, soil temperature and moisture interactions had a significant impact on CH_4 emissions in alpine marshes and peat wetlands (Gao et al., 2011). The variations may result from the differences in soil types (Tian et al., 2010), soil properties (Li et al., 2020) and soil moisture (Yang et al., 2013).

Global warming potential converts the elevating temperature effect of a certain greenhouse gas in a certain time range into equivalent CO_2, which can quantitatively assess the effect of greenhouse gas on climate warming. We found that soil CO_2 emissions were the main contribution of GWP (above 84.93%), followed by N_2O (Table 2). A previous study reported that CO_2 emissions accounted for 94–100% and 75–85% of the GWP in mineral and organic wetland soils, respectively (Bonnett et al., 2013). Huang et al. (2019) found that CO_2, CH_4 and N_2O contributed 20%, 10% and 70% to the GWP of artificial tidal mangrove wetlands, respectively. One study even found that CH_4 emissions accounted for 68% of the GWP in natural mangrove wetlands (Wang et al., 2016).

In the present study, increasing temperature significantly increased the GWP, which was 2.85 times higher in T_{20} than in T_5 (Table 1), suggesting that the GWP has positive feedback to climate warming. Similar results were also found in other studies in which the GWP at 20°C was 2.8 times higher than that at 5 °C in Alaskan peat wetlands (Treat et al., 2014) and 2.1 times higher at 19°C than at 7°C in Tibetan alpine wetlands (Liu et al., 2017). Correlation analysis indicated that temperature and moisture affected GWP mainly by affecting soil pH, organic matter, nitrogen availability and enzyme activity (Figure 4A). Hydrothermal factors and soil properties together accounted for 85.93% of GWP variations (Figure 4B), suggesting that GWP is not only regulated by soil temperature and moisture interactions but also affected by soil chemical properties. Li et al. (2020) found that soil environmental variables account for 28%–67% of GHG emission changes in coastal wetlands. Environmental variables could explain 58.58% of the change in carbon concentration under elevated temperature conditions in paddy wetlands and natural wetlands (Furlanetto et al., 2018). Our results supported that GHG emissions are not only affected by temperature and moisture but also regulated by soil properties and enzyme activities (Salimi et al., 2021).

5 Conclusion

Increasing temperature and moisture significantly promoted CO_2 and N_2O emissions, and CH_4 emissions increased with increasing moisture. There was a decrease in the contribution of CO_2 but an increase in the contribution of N_2O to the GWP with increasing temperature and moisture. The CO_2 and N_2O emissions and GWP were positively correlated with urease activity and negatively correlated with soil pH, SOM and catalase. Soil CH_4 emissions were positively correlated with MBC and MBN. The hydrothermal changes (temperature and moisture), soil properties and their interaction explained 26.86%, 9.46% and 49.61% of the variations in GWP, respectively, suggesting that the temperature and moisture interaction had a direct effect on GHG emissions and an indirect effect by regulating soil properties.

Data availability statement

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

Author contributions

YH: Data processing and analysis, manuscript writing TZ: Funding acquisition, Data analysis, Manuscript writing and editing QZ: Gas measurements and data sorting XG: Data curation supporting, Formal analysis supporting TH: Resources supporting SY: Gas measurements.

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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.

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