



Extrapolation and Uncertainty Evaluation of Carbon Dioxide and Methane Emissions in the Qinghai-Tibetan Plateau Wetlands Since the 1960s

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Wetlands are important modulators of atmospheric greenhouse gas (GHGs) concentrations. However, little is known about the magnitudes and spatiotemporal patterns of GHGs fluxes in wetlands on the Qinghai-Tibetan Plateau (QTP), the world's largest and highest plateau. In this study, we measured soil temperature and the fluxes of carbon dioxide (CO₂) and methane (CH₄) in an alpine wetland on the QTP from April 2017 to April 2019 by the static chamber method, and from January 2017 to December 2017 by the eddy covariance (EC) method. The CO₂ and CH₄ emission measurements from both methods showed different relationships to soil temperature at different timescales (annual and seasonal). Based on such relationship patterns and soil temperature data (1960–2017), we extrapolated the CO₂ and CH₄ emissions of study site for the past 57 years: the mean CO₂ emission rate was 91.38 mg C m⁻² h⁻¹ on different measurement methods and timescales, with the range of the mean emission rate from 35.10 to 146.25 mg C m⁻² h⁻¹, while the mean CH₄ emission rate was 2.75 mg C m⁻² h⁻¹, with the ranges of the mean emission rate from 1.41 to 3.85 mg C m⁻² h⁻¹. The estimated regional CO₂ and CH₄ emissions from permanent wetlands on the QTP were 94.29 and 2.37 Tg C year⁻¹, respectively. These results indicate that uncertainties caused by measuring method and timescale should be fully considered when extrapolating wetland GHGs fluxes from local sites to the regional level. Moreover, the results of global warming potential showed that CO₂ dominates the GHG balance of wetlands on the QTP.

Keywords: climate change, wetlands, greenhouse gas, carbon fluxes, global warming potential

INTRODUCTION

Since the beginning of the Industrial Era, large amounts of greenhouse gases (GHGs) have been released into the atmosphere (Boden et al., 2011). The continuously increasing concentrations of GHGs, particularly carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), contribute to the rise of land and ocean surface temperatures globally (IPCC, 2013). The trend of global warming will undoubtedly lead to changes in ecosystem structure, processes and functions in the next decades (Kintisch and Buckheit, 2006).

Although the increasing concentration of GHGs in the atmosphere is due mainly to human activities, about one third derives from natural resources, such as wetland soils (Marin-Muniz et al., 2015). Wetlands are unique in that they are formed by the interaction of terrestrial and aquatic ecosystems (Lewis and Ebrary, 1995). This allows them to serve many important functions, including improving water quality and micro-climate, sequestering carbon, and protecting biodiversity (Costanza et al., 1997; Engelhardt and Ritchie, 2001; Lamers et al., 2014). The wetlands occupy only 5–8% of land areas on Earth, but they store more than 30% of the world's soil carbon (Bridgman et al., 2012; Malone et al., 2013). Especially, in high-latitude wetlands, the combination of high productivity and low decomposition has resulted in significant carbon storage (Whiting and Chanton, 2001). Wetlands are considered as a major source of GHGs emissions (Bridgman et al., 2012; Mitsch et al., 2013). Therefore, quantifying and modeling the emission of GHGs from wetlands is very important for understanding the impacts of climate change on terrestrial ecosystem processes (Liu et al., 2017).

Many studies identified the production of GHGs in wetlands generally depends on soil temperature, water tables and redox conditions (Inglett et al., 2012; Treat et al., 2014). Soil temperature may impact the gaseous diffusivity of surface soils, soil organic matter decomposition, chemical reaction rates and so on, which ultimately impact GHGs emissions in wetlands (Liu et al., 2017; Yu et al., 2017). Although some studies have evaluated the relationships between GHGs fluxes and different environment factors in wetland, they are still uncertain in different wetlands. For example, a strong correlation between GHGs fluxes and soil temperature was found in artificial wetlands (Liu et al., 2013), but weak correlations were found in northern wetlands (Yu et al., 2017). Therefore, more *in situ* observations are still needed in wetlands.

The Qinghai-Tibetan Plateau (QTP), also known as the “Third Pole” of the Earth, is the largest and highest plateau in the world, with an average altitude of about 4 km. About 25% of the plateau's area of 2.5×10^6 km² (Chen et al., 2013a) is covered in wetlands (Hirota et al., 2004; Lehner and Doell, 2004; Niu et al., 2012; Chen et al., 2014; Wei and Wang, 2016). Since the 1960s, the QTP has experienced substantial changes due to human activities and natural processes, such as climate warming, water pollution and degradation of grassland and wetland (Piao et al., 2010; Chen et al., 2013b; Gao et al., 2013). The temperature of QTP has increased by 0.2°C per decade, faster rate than the global average of 0.74°C over the last century (Chen et al., 2013b; Liu et al., 2017). Climate changes are likely to affect the

carbon and nitrogen cycles of alpine wetlands on the QTP (Gao et al., 2009; Tang et al., 2009; Zeng et al., 2017). Therefore, studying the GHGs fluxes in the QTP wetlands is necessary, which will further our understanding of carbon dynamics, as well as provide crucial insight into wetland responses to climate change. Although several studies estimated the dynamic and budget of carbon on the QTP, significant uncertainties of the size and the spatial distribution of carbon still exist when estimating current and future GHGs emissions from wetlands (Chen et al., 2013a; Jin et al., 2015; Wei and Wang, 2016; Cao et al., 2017; Zhang et al., 2020). There is a need for long-term field measurements to quantify carbon dynamics in wetlands under various climatic conditions (Zhao et al., 2006). And to evaluate the differences from different methods at different temporal-spatial scales will contribute to accurately quantify the budget of carbon of wetlands on the QTP.

In the present study, we measured the GHGs (CO₂ and CH₄) exchange between the atmosphere and wetland ecosystem on the QTP by the manual static chamber-gas chromatography method and the eddy covariance (EC) method. We aimed to (1) investigate spatiotemporal variations in CO₂ and CH₄ fluxes between soil and atmosphere and their relationship with soil temperature in the wetlands of the QTP, and (2) assess the uncertainties in extrapolation of CO₂ and CH₄ emissions from wetlands on the QTP.

MATERIALS AND METHODS

Study Site

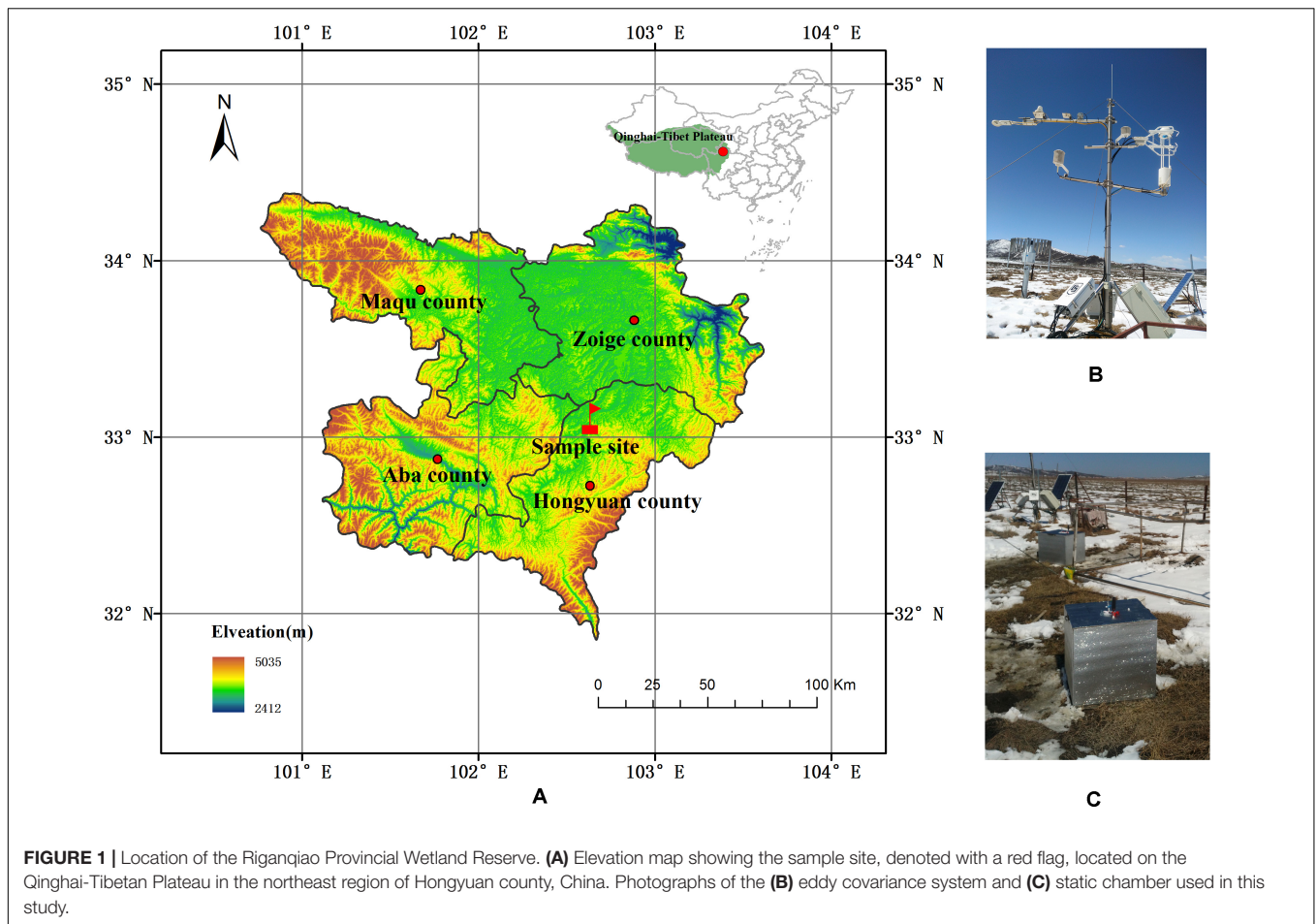
The study was conducted at the Riganqiao Provincial Wetland Reserve (33°06'25" N, 102°38'33" E) located in the National Nature Reserve of Hongyuan county, China (**Figure 1**). The study site lies in the northeastern region of the QTP. The alpine wetland has an annual average temperature of 1.5°C and annual average precipitation of 270 mm (Liu et al., 2016; Zhong et al., 2017). The dominant vegetation is herbaceous plants, including *Carex mulinesis*, *Trollius farreri*, *Gentiana formosa*, and *Caltha palustris* (Yang et al., 2014; Liu et al., 2016; Zhong et al., 2017).

Gas Flux Measurements and Calculations

We performed *in situ* measurements primarily using the manual static chamber-gas chromatography method, already used to study most natural ecosystems (Chen et al., 2013a; Marin-Muniz et al., 2015; Wei and Wang, 2016). The eddy covariance (EC) method, a micrometeorological approach widely was applied to continuously measure carbon exchange between the atmosphere and ecosystems (Yu et al., 2017; Cui et al., 2018).

Chamber Method

GHGs fluxes were measured with static chamber method *in situ* from April 2017 to April 2019. The base of the stainless steel chamber (50 × 50 × 50 cm) was embedded 10 cm into the soil. To begin sampling, the base was filled with water to seal the compartments from outside air. Four



static chambers were established on the study site. Four air samples were collected per hour from each chamber, which were taken at 10 min intervals after enclosure, stored in 10 ml air-tight vacuum vials. We took eight measurements from 10:00 to 18:00. Eight GHGs fluxes were collected for each chamber and the average value of four chambers was taken as the monthly emission value. No measurements were taken in February because weather conditions blocked access to the sample site. Temperature was recorded during gas sampling by sensors positioned on the inside and outside of the chamber and connected to an electronic thermometer. The GHGs concentrations were analyzed by gas chromatography (7890A GC System, Agilent Technologies, United States) (Chen et al., 2013a).

The fluxes of CO₂ and CH₄ were calculated as:

$$F = H \cdot \frac{M}{V_0} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \cdot \frac{dc}{dt} \quad (1)$$

where F is gas flux; H, chamber height above the soil surface; M, molar mass of gas; V₀, standard molar volume (22.4 L mol⁻¹); P, atmospheric pressure at the sampling site; P₀, atmospheric pressure (101,325 Pa); T₀, absolute temperature of 0°C (273.15 K); T, the absolute temperature of the sampling time and dc/dt, change in gas flux rate. Details regarding the

calculation of gas fluxes have been described (Chen et al., 2013a; Marin-Muniz et al., 2015).

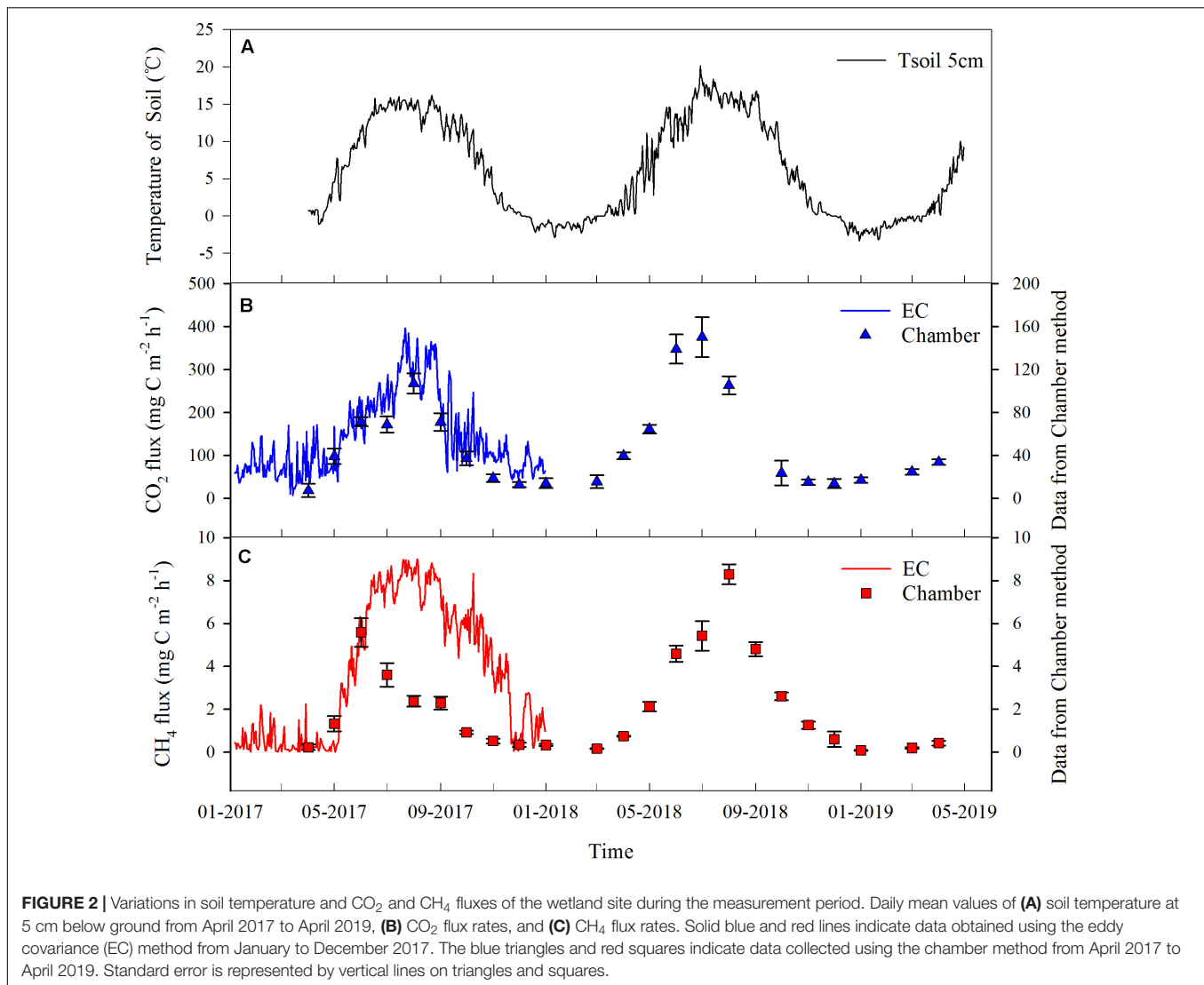
EC Method

The CH₄ fluxes were measured from January 2017 to December 2017 using the open-path EC method at a height of 2.5 m (Figure 1). Flux data were recorded at 10 Hz and logged at 30-min intervals using a data logger (CR3000; Campbell Scientific, United States). The raw CH₄ data were postprocessed and quality controlled by EddyPro v4.2 software¹ to compute the CH₄ fluxes over an half hour interval (Foken et al., 2004). Due to missing and discarded data, in this study, we filled the gaps of CH₄ data by an average diurnal variations based on previous and subsequent days. Details of the CO₂ data processing have been described in previous study (Liu et al., 2019).

Soil Temperature Measurements *in situ*

Soil temperature was automatically recorded at 30-min intervals by sensors (WatchDog-B101, Spectrum, Chicago, United States) placed 5 cm below the soil surface at the sample site. Further investigation was conducted to explore

¹<https://www.licor.com>



the relationships between soil temperature at 5 cm of depth and GHGs emissions.

Additional Data Sources and Preprocessing

Wetland distribution maps (1980, 1990, 2000, and 2008) were acquired from Niu et al. (2009), which had been widely used in wetland classification and ecological regionalization (Liu et al., 2015; Zhu et al., 2016; Wang et al., 2020). In this study, the area overlapping across all four wetland distribution maps was defined as permanent wetland. Grid monthly soil temperatures at a depth of 5 cm (1960–2017) of QTP was extracted from the soil temperature dataset of China, which was constructed by interpolation at a spatial resolution of 5 arc-min using ANUSPLIN based on soil temperature data at a depth of 5 cm of 650 national meteorological stations that obtained from the China Meteorological Data Service Center².

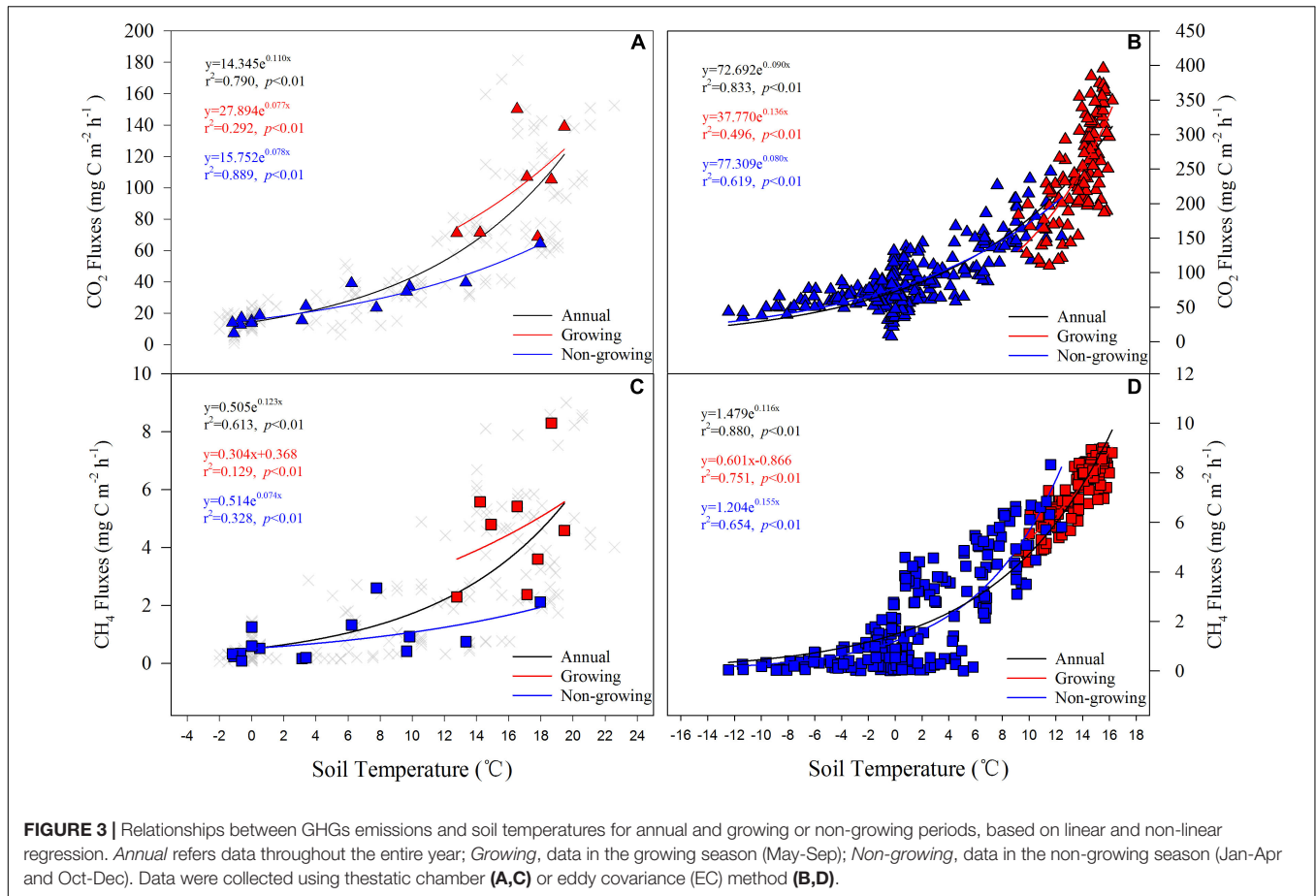
²<http://data.cma.cn/>

Statistical Analyses

Mean emissions of CO₂ and CH₄ were calculated by averaging the replicates of sampling data. Soil temperature was calculated by averaging daily data. Linear and non-linear regressions were used to evaluate the relationship between soil temperatures and GHGs fluxes as measured by both methods (static chamber or EC) at different timescales (annual and seasonal). Results from the best fitting regression models are presented. All statistical analyses were performed using the software package R (R Core Team, 2020).

Extrapolation of GHGs Fluxes

The relationship between soil temperature of 5 cm depth and observed CO₂ and CH₄ emissions was explored at different timescales [annual, non-growing (Jan–Apr and Oct–Dec) or growing season (May–Sep) (NG&G seasonal)]. Then the regression equations were applied to extrapolate the CO₂ and CH₄ emission rates of study site from 1960 to 2017 and the uncertainties were investigated.



In addition, the regression equations from EC method at NG&G seasonal timescales was performed for each wetland grid cell in order to roughly evaluate the long-term total and spatial patterns of wetland CO₂ and CH₄ emissions on the whole QTP.

RESULTS

Soil Temperature During Measurements

The daily average soil temperature at a depth of 5 cm ranged from -3.35 to 20.13°C during the entire observation period (April 2017–April 2019) (Figure 2A). Soil temperature showed a clear seasonal variation, with higher temperatures recorded during the growing season (from June–September) than during the non-growing season in 2017 and 2018. Daily mean temperatures were often below zero in winter (December–February), when soil layers were frozen.

Seasonal Dynamics of CO₂ and CH₄ Fluxes

The CO₂ fluxes showed a typical seasonal pattern: high fluxes were measured during the plant growing season, and low fluxes during the non-growing season (Figure 2B). The EC

method showed greater variability in CO₂ fluxes than the chamber method. Measurements by the EC method oscillated between 7.38 and 395.74 mg C m⁻² h⁻¹. The CO₂ fluxes from the chamber method oscillated between 7.21 ± 6.20 and 150.15 ± 18.73 mg C m⁻² h⁻¹. Peak CO₂ fluxes were registered in August 2017 by both methods (EC: 395.74 mg C m⁻² h⁻¹; chamber: 106.94 ± 9.29 mg C m⁻² h⁻¹). However, only the chamber method found another peak flux in July 2018 (150.15 ± 18.73 mg C m⁻² h⁻¹), as the EC method did not capture data after 2017. Peaks in CO₂ fluxes usually coincided with peaks in soil temperature.

The seasonal dynamics of CH₄ fluxes paralleled those of CO₂ fluxes. The CH₄ emission rate measured by the EC method oscillated between 0.01 and 9.00 mg C m⁻² h⁻¹, while the rate from the chamber method ranged from 0.08 ± 0.02 to 8.30 ± 0.46 mg C m⁻² h⁻¹ (Figure 2C). The EC method measured a higher CH₄ emission rate than the chamber method from May to December 2017. The chamber method captured emission spikes in July 2017 and August 2018. Although CH₄ emission rates exhibited similar dynamics as soil temperature, they slowed down in June 2017 (2.38 ± 0.25 mg C m⁻² h⁻¹) and August 2017 (2.30 ± 0.30 mg C m⁻² h⁻¹), despite increasing soil temperature. The winter season also slowed the rate of methane emissions.

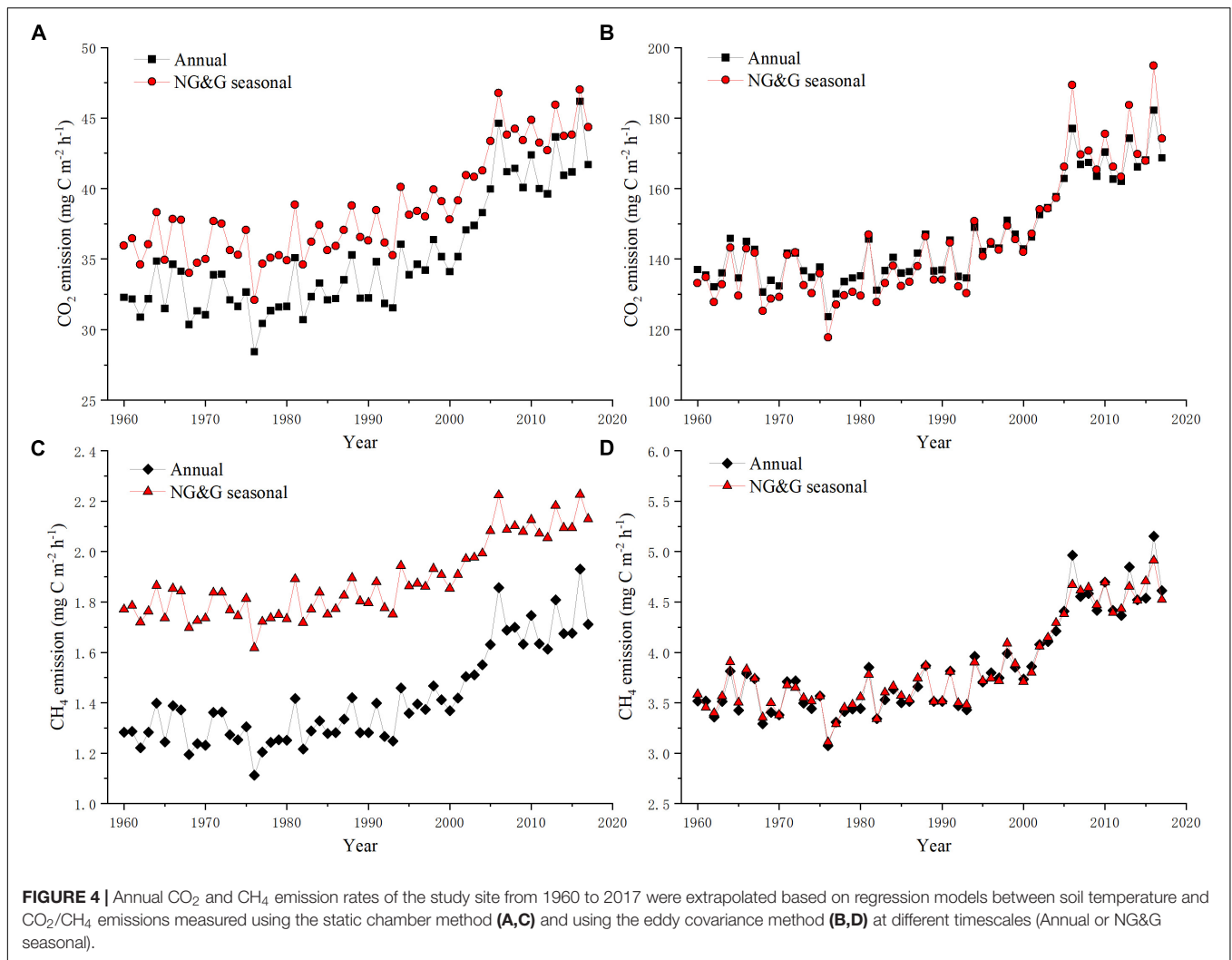


TABLE 1 | Extrapolated mean emission rate of CO₂ and CH₄ of study site for the period 1960–2017, based on models derived from data obtained using the chamber or EC method at different timescales*.

Emission rate (mg C m ² h ⁻¹)	Measurement method	Annual	NG&G seasonal	Average
CO ₂	Chamber	35.10	38.60	91.38
	EC	146.25	145.58	
CH ₄	Chamber	1.41	1.88	2.75
	EC	3.85	3.85	

*Timescales were the entire year (Annual), non-growing season and growing season (NG&G seasonal). Abbreviations: Chamber, static chamber; EC, eddy covariance.

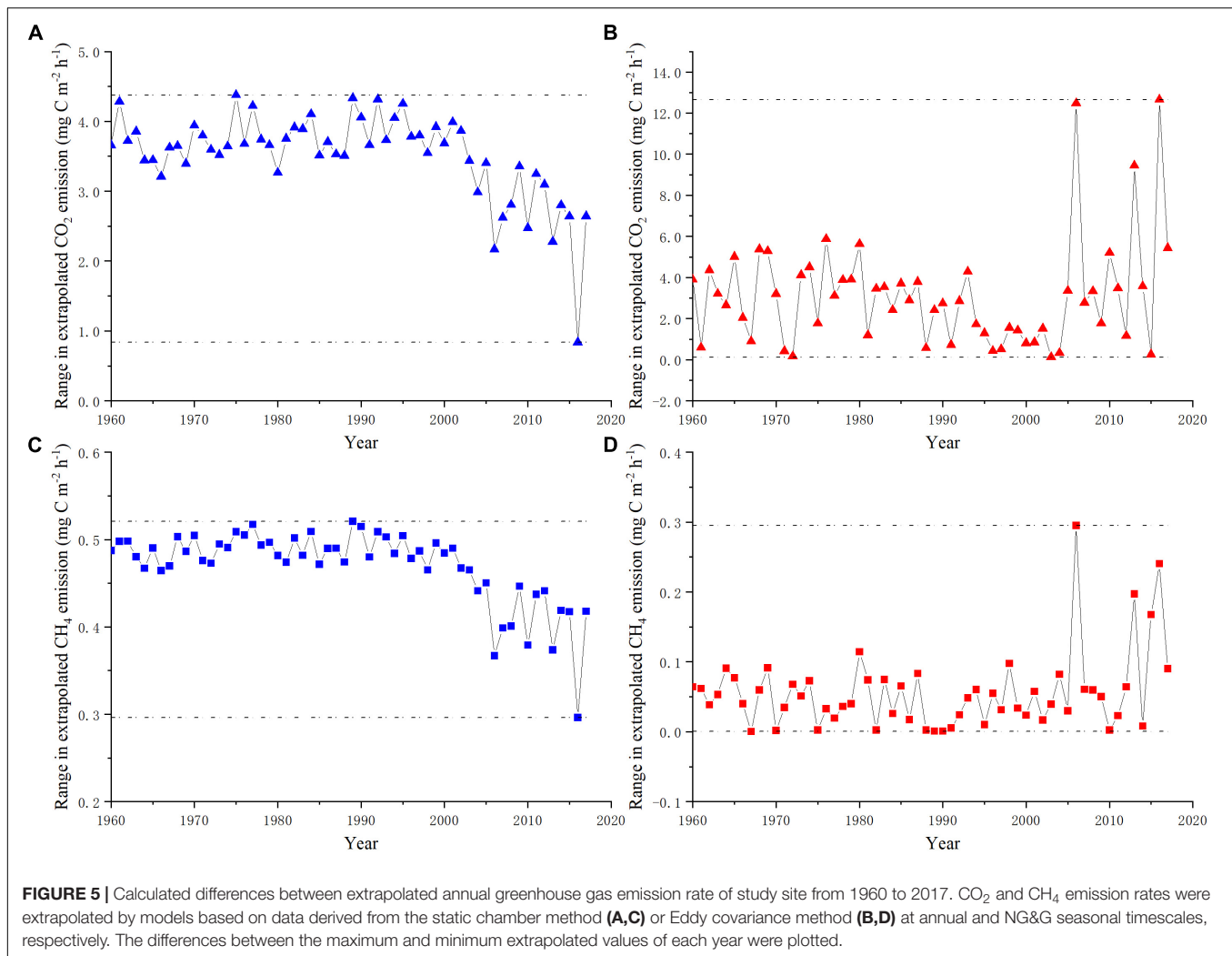
Relationship of CO₂ and CH₄ Fluxes to Soil Temperature

According to regression analyses, CO₂ fluxes increased exponentially with rising soil temperatures based on both EC and chamber measurements. Likewise, positive exponential correlations were found between CO₂ fluxes and soil temperatures during growing season or non-growing season (Figures 3A,B). The CH₄ fluxes correlated well with soil temperatures based on both methods. We also found positive relationships between CH₄ fluxes and soil temperatures. The relationship between CH₄ emission and

soil temperature was exponential during the non-growing season but linear relationship was found during the growing season (Figures 3C,D).

Extrapolation of CO₂ and CH₄ Emission Rates of the Study Site

Based on the soil temperatures of study site and the regression equations, we extrapolated the CO₂ and CH₄ emission rates of the study site for the last 57 years (Figure 4). For static chamber method, extrapolated GHGs emission rates were higher for regression equations based



on the NG&G seasonal scale than for equations based on the annual scale (Figures 4A,C). For the EC method, extrapolated GHGs emission rates are similar at both timescales (Figures 4B,D).

Although extrapolated CO₂ emission rate followed similar trends whether based on the static chamber method or the EC method, the two methods gave significantly different magnitudes for the emission rate. The CO₂ emission rate in the static chamber method was far less than that measured by the EC method (Figures 4A,B). Extrapolated mean CO₂ emission rate of study site from 1960 to 2017 was calculated to be 91.38 mg C m⁻² h⁻¹, with the ranges of the mean emission rate from 35.10 to 146.25 mg C m⁻² h⁻¹ on different measurement methods and timescales (Table 1). The differences of emission rates between the maximum and minimum values extrapolated for each year reflected uncertainties from the same measurement method at different timescales. Uncertainties in extrapolation of the CO₂ emission rates ranged from 0.84 to 4.38 mg C m⁻² h⁻¹ based on static chamber data, and from 0.13 to 12.67 mg C m⁻² h⁻¹ based on EC data (Figures 5A,B).

Extrapolated values for CH₄ emission rate based on EC data were three times larger than extrapolated values based on chamber data (Figures 4C,D). Extrapolated mean CH₄ emission rate of the study site was 2.75 mg C m⁻² h⁻¹ from 1960 to 2017, with the ranges of the mean emission rate from 1.41 to 3.85 mg C m⁻² h⁻¹ on different measurement methods and timescales (Table 1). Differences in annual average maxima and minima reflected uncertainties from static chamber method data ranging from 0.30 to 0.52 mg C m⁻² h⁻¹ (Figure 5C), while uncertainties in data extrapolated from the EC method ranged from 0 to 0.30 mg C m⁻² h⁻¹ (Figure 5D).

Regional Extrapolation of CO₂ and CH₄ Emissions From Wetlands on the QTP

Based on spatial soil temperature dataset of wetlands and the regression equations from EC method at NG&G seasonal timescales, total GHGs emissions of permanent wetland on the QTP were roughly extrapolated by performing the model for each wetlands grid cell. The CO₂ and CH₄ emissions of wetlands

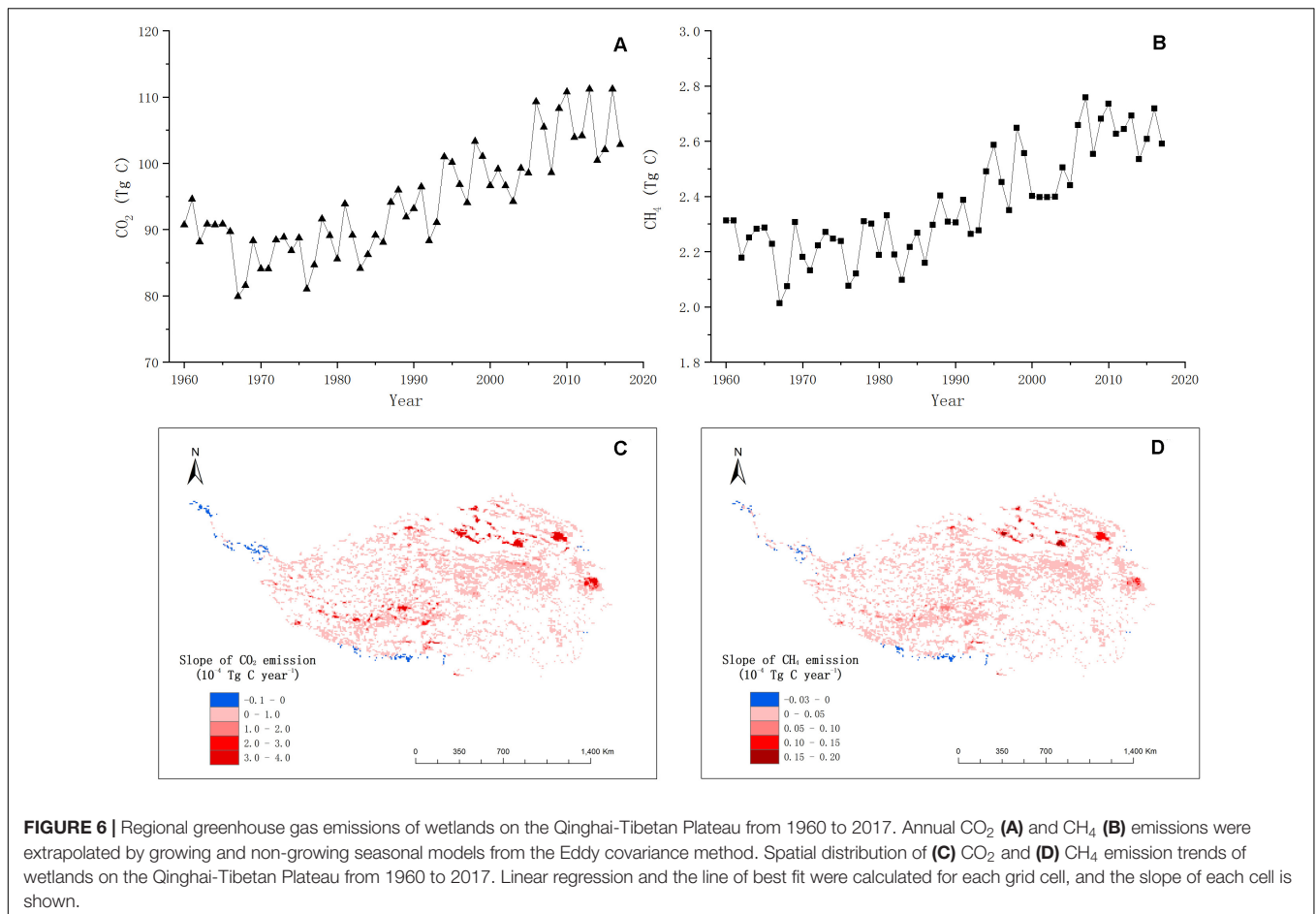


TABLE 2 | Estimated greenhouse gas emissions from the Qinghai-Tibetan Plateau wetlands in the literature.

CO ₂ Tg C year ⁻¹	Method	Period	References	CH ₄ Tg C year ⁻¹	Method	Period	Wetland Area × 10 ⁴ km ²	References
40.65	Extrapolation	2011–2013	Cao et al., 2017	0.53–0.68	Extrapolation	1996–1997	18.8	Jin et al., 1999
58.34	Extrapolation	2008–2009	Hao et al., 2011	0.42	Extrapolation	2001–2002	5.52	Ding et al., 2004
94.29	Regression model	2010–2017	This study	0.17–0.31	Extrapolation	2012–2014	6.32	Wei et al., 2015
				1.12	Meta-Analysis	2000		Chen et al., 2013c
				1.85	Model	1995–2005	11.5	Xu et al., 2010
				0.71	Model	2001–2011	13.4	Jin et al., 2015
				0.59–8.55	Model	1980–2010	1.2–9.8	Wei and Wang, 2016
				0.17	Model	2000–2010	3.33	Li et al., 2016
				0.18–0.27	Model	1978–2008	10.0	Zhang et al., 2020
				2.37	Regression model	2010–2017	7.1	This study

displayed pronounced increase on the whole QTP from 1960 to 2017 (Figures 6A,B). And the growth tendencies of CO₂ and CH₄ emissions showed no significant spatial heterogeneity on the QTP (Figures 6C,D). The northern part of the QTP showed the most obvious increase, while the marginal region displayed a downward trend. Moreover, we examined previously published

results on CO₂ and CH₄ emissions from the QTP wetlands and compared them with average values extrapolated from 2010 to 2017 in the present study (Table 2). Calculated the regional CO₂ emission (94.29 Tg C year⁻¹) of wetlands on the QTP were higher than the ranges reported in the literature (40.65–58.34 Tg C year⁻¹). And the CH₄ emission (2.37 Tg C year⁻¹) of wetlands

on the QTP in this study fell within the range of previous studies (0.17–8.56 Tg C year⁻¹) (Table 2).

The GWP was applied to determine the relative and total contributions of CO₂ and CH₄ to the greenhouse effect. CH₄ values were converted to CO₂-equivalents based on published calculations (Kandel et al., 2019). From 1960 to 2017, the CO₂ emissions contributed the largest amount to carbon balance and dominated the atmospheric GHGs balance on the wetlands of the QTP. The CO₂ contributed approximately four times more than CH₄ to the GHGs balance on QTP wetlands (Figure 7A). The ratio of CH₄ to CO₂ emissions across all wetlands of the QTP has slightly declined in the past 57 years, despite significant increases in emissions of both gases (Figure 7B).

DISCUSSION

Relationships Between GHGs Fluxes and Soil Temperatures *in situ*

The wetland ecosystem of QTP is an important natural emitter of GHGs. The CO₂ and CH₄ fluxes showed similar seasonal emission patterns, with the greatest emissions noted during the plant growing season (Chen et al., 2013b; Liu et al., 2017). In this study, the CO₂ and CH₄ emissions were positively related to soil temperature, as reported for other wetlands (Zhao et al., 2006; Marin-Muniz et al., 2015).

The effects of soil temperature on CO₂ fluxes depend strongly on the availability of oxygen within the soil (Bonnett et al., 2013; Gao et al., 2013). Oxygen is an important factor that regulates organic matter decomposition in soil and the release of CO₂ (Bonnett et al., 2013; Treat et al., 2014; Liu et al., 2017). During the non-growing season on the QTP wetlands, the soil temperature was below freezing, which may inhibit the transport of oxygen from the soil to the rhizosphere zone, resulting in low CO₂ flux. Furthermore, soil temperature may also indirectly affect CO₂ fluxes by influencing rates of substrate supply, transport, and chemical reactions, which ultimately

affect the release of CO₂ from wetland soil (Treat et al., 2014; Wei and Wang, 2016).

CH₄ emissions depend on anaerobic (production) and aerobic (oxidation) processes (Liu et al., 2017; Wei and Wang, 2017). Wetlands provide good anaerobic environments, and higher temperatures can promote activity of microbes such as methanogens. Both factors significantly increase CH₄ production in soil (Inglett et al., 2012). Furthermore, changes in soil temperature can also stimulate CH₄ transport from soil into the atmosphere (Yvon-Durocher et al., 2011). This transport slows in winter when soil temperature drops and CH₄ becomes trapped under a layer of ice, allowing only a small portion to be oxidized. As ice thaws during the following growing season, the stored CH₄ gas is released into the atmosphere. This cycle may partly explain the large CH₄ emission from the QTP wetlands during warm seasons. Thus, CH₄ emission appears to depend strongly on seasonal changes in the local environment, especially the influence of soil temperature on gas exchange.

Uncertainties in Extrapolation of GHGs Emission Rates of Study Site

With wetland soil temperatures and regression equations, we extrapolated the CO₂ and CH₄ emission rates of the study site. At different time scales, the GHGs emission rates extrapolated using static chamber measured data had higher uncertain than using EC measured data. The GHGs emission rates extrapolated by EC method were consistent under both time scales (Figure 4).

Measurement methods might result in the difference of estimated emission rates. The carbon balance of wetlands located in high latitude regions is strongly related to microtopography (Sullivan et al., 2008; Li et al., 2017). Although the wetland's topography and ecosystem appear to be flat and homogeneous, there is a significant amount of spatial heterogeneity at finer scales (a small chamber) or larger scales (the sample site). GHGs fluxes measured with the static chamber method cover only small patches of soil, which are usually not sufficient to make a full-scale understanding of the carbon exchanges of the heterogeneous ecosystems (Song et al., 2015). The EC method measured the

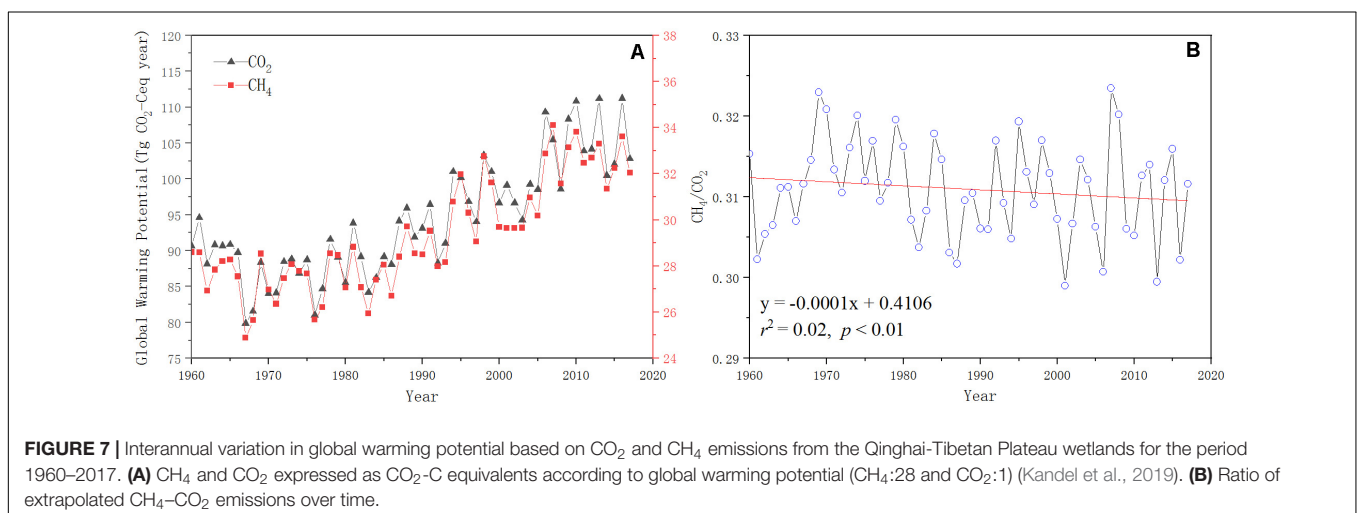


FIGURE 7 | Interannual variation in global warming potential based on CO₂ and CH₄ emissions from the Qinghai-Tibetan Plateau wetlands for the period 1960–2017. **(A)** CH₄ and CO₂ expressed as CO₂-C equivalents according to global warming potential (CH₄:28 and CO₂:1) (Kandel et al., 2019). **(B)** Ratio of extrapolated CH₄–CO₂ emissions over time.

carbon exchange between the atmosphere and ecosystems over a large area. Neglecting the effect of spatial heterogeneity might lead to the difference of GHGs emission rate that resulted in larger variance during extrapolation (Li et al., 2017). In addition, the static chamber method introduces so-called “chamber effects,” potentially including modifications of temperature and moisture within the chamber as well as changes in the gas diffusion gradient within the soil profile (Song et al., 2015). The EC method, for its part, is susceptible to intermittent turbulence exchanges, commonly occurring at night, which reduce data quality (Gu et al., 2005; Aubinet et al., 2012; Yu et al., 2017). These limitations may also lead to uncertainties in extrapolated data.

The uncertainties of extrapolated emission rate resulted from the differences of regression models at different timescales. There were linear or non-linear correlations between soil temperature and GHGs fluxes in wetlands in previous studies (Kato et al., 2005; Liu et al., 2013; Song et al., 2015; Yu et al., 2017). Soil temperature has proven to be one of the most important factors affecting GHGs emission, but hydrology, plants, and soil microorganism also have an impact (Bhullar et al., 2013; Marin-Muniz et al., 2015). Particularly in wetlands, GHGs emissions are affected by many complex ecological processes, such as soil carbon and nitrogen cycling and root respiration (Baldock et al., 2012; Liu et al., 2013). All these factors are subject to seasonal and temperature-related changes. For example, during the plant non-growing season, plants begin wilting and gradually lose their ability to transport gas via stomata, and the upper soil and water layers freeze. These seasonal changes alter soil temperature and, consequently, the emission of GHGs (Song et al., 2015). This difference may also reflect the influence of fluctuations in soil temperature and water level. The water level not only limits the oxygen concentration but also influences soil temperature by controlling thermal conductivity (Yu et al., 2017). During the plant growing season, abundant precipitation influences both soil thermal and hydrological conditions, including water table depth, soil temperature and thawing depth. Heat is carried to deeper layers of soil by infiltration, rather than by thermal conduction, due to the low thermal conductance of the wetland and the high efficiency of water infiltration. This heat increases the soil temperature, promoting the thawing of the bottom permafrost. Thus, the rising temperature due to climate change and rising water level due to increased precipitation likely stimulate GHGs emission from wetlands beyond what would occur due to increases in either soil temperature or water level alone (Song et al., 2015). This may explain why, in the present study, the different correlations between soil temperature and the GHGs emission rate were found in different timescales.

Uncertainties in Regional Extrapolation of GHGs Emissions of Wetlands on the QTP

For the whole QTP, we extrapolated regional GHGs emissions from permanent wetlands by the seasonal model calculated EC method. The regional CO₂ emission was higher than the ranges reported in the literature, but the CH₄ emission fell within the ranges of previous studies. The uncertainties of estimation may result from inaccuracies in the wetland area. Jin reported

the earliest estimates of CH₄ emissions ranging from 0.53 to 0.68 Tg C year⁻¹, based on observations (Jin et al., 1999). Wei made a challenge estimation of CH₄ emissions by integrating a biogeochemical model, which considered the wetland extents, and suggested that previous studies might have underestimated CH₄ emissions, due to bias in wetland extents (Wei and Wang, 2016). Currently, the wetland area on the QTP ranges from 1.2 to 18.8 × 10⁴ km² (Jin et al., 1999; Niu et al., 2009, 2012; Zhang et al., 2020). A large discrepancy of wetland extent products largely affects estimations of GHGs emissions from natural wetland (Wei and Wang, 2016). Thus, improving the ability to obtain accurate data on the distribution and extent of wetlands should be a research priority in the future (Li et al., 2016). In addition, the spatial dataset of soil temperature was obtained by the spatial interpolation method, and its uncertainty might also lead to differences of estimated the total GHGs emissions from wetlands on the QTP. Therefore, the impact of these factors should be taken into account when estimating the GHGs emissions from the QTP wetlands, which will improve our understanding of the role of natural wetlands in the GHGs budget.

Spatial Distribution and GWP of GHGs Emissions of Wetlands on the QTP

Since the 1960s, the QTP has experienced universal and significant warming, heating up by 0.2–0.5°C per decade (Piao et al., 2010; Chen et al., 2013b). Projections of the Intergovernmental Panel on Climate Change showed that this warming trend will continue (IPCC, 2013). It is highly likely this will set up a positive feedback loop in the wetlands, in which warmer climate drives release of more GHGs, which in turn will raise the temperature (Song et al., 2015). Although the absolute amounts of CH₄ emitted are small compared to the amounts of CO₂, CH₄ contributes 28 times more than CO₂ to the atmospheric absorption of infrared radiation (Kandel et al., 2019). Previous studies have shown that CO₂ fluxes may mitigate the impact of CH₄ fluxes (Whiting and Chanton, 2001; Mitsch et al., 2013). The ratio of CH₄ fluxes to CO₂ fluxes may serve as an important index for an ecosystem's GHGs exchange balance with the atmosphere (Whiting and Chanton, 2001; Malone et al., 2013). For the entire wetlands of the QTP, the CO₂ emissions dominated the carbon balance in the wetland ecosystem and the GHGs balance in the atmosphere. We calculated a declining ratio of CH₄ to CO₂ for the period 1960–2017, indicating that CO₂ has become the main contributor to total GHGs fluxes. Thus, without human interference, the GHGs exchange balance should remain relatively constant on the wetlands of the QTP in the future.

CONCLUSION

The alpine wetland ecosystem in the QTP is an important source of GHGs. GHGs emissions vary exponentially with soil temperature. The CO₂ dominates the GHGs balance on QTP wetlands. Extrapolating GHGs fluxes from local to regional levels involves substantial uncertainties that depend on the measurement technique, timescale and wetlands extent. These parameters should be taken into consideration to ensure accurate estimation of GHGs fluxes in future research.

DATA AVAILABILITY STATEMENT

Monthly CO₂ and CH₄ flux data and soil temperature data presented in this article will be archived and freely available from figshare, doi: 10.6084/m9.figshare.12703121.v3.

AUTHOR CONTRIBUTIONS

QZ conceived and designed research. JZ, XL, ZY, and LJ collected data and conducted research. JZ and MY wrote the initial

manuscript. HC, CB, MW, and PZ revised the manuscript. All authors read and approved the final manuscript.

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

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