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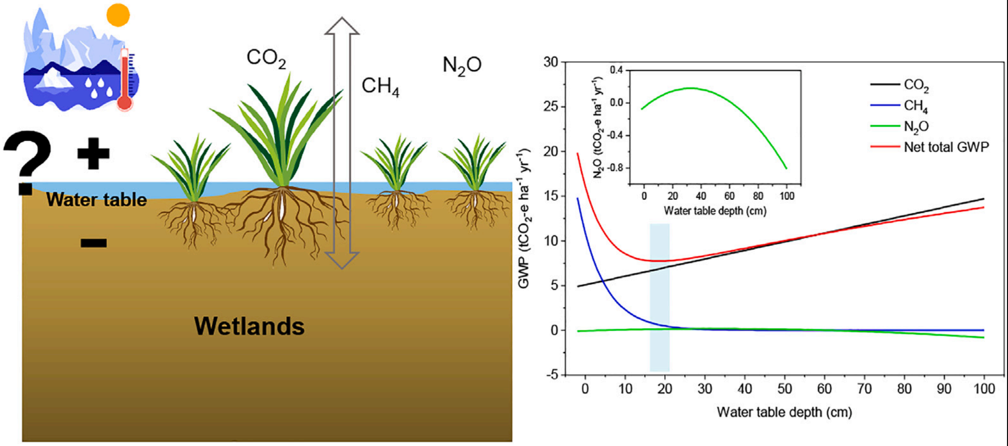

Jiang Zhang, Huai Chen, Meng Wang, ..., Le Wang, Dongxue Yu, Qiuan Zhu

zhuq@hhu.edu.cn

Highlights

Typical wetland in Qinghai-Tibetan Plateau shows positive global warming potential

A water table depth of ~18 cm was optimal for mitigating GWP in the wetland of QTP

Water table management would be effective in mitigating future GHGs from wetland of QTP

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An optimized water table depth detected for mitigating global warming potential of greenhouse gas emissions in wetland of Qinghai-Tibetan Plateau

Jiang Zhang,[1,2] Huai Chen,[3] Meng Wang,[4] Xinwei Liu,[3] Changhui Peng,[5,8] Le Wang,[6] Dongxue Yu,[6] and Qiuan Zhu[1,7,9,*]

SUMMARY

Climate change and human activities have intensified variations of water table depth (WTD) in wetlands around the world, which may strongly affect greenhouse gas emissions. Here, we analyzed how emissions of CO_2, CH_4, and N_2O from the Zoige wetland on the Qinghai-Tibetan Plateau (QTP) vary with the WTD. Our data indicate that the wetland shows net positive global warming potential (11.72 tCO_2-e ha^{-1} yr^{-1}), and its emissions of greenhouse gases are driven primarily by WTD. Our analysis suggests that an optimal WTD exists, which at our study site was approximately 18 cm, for mitigating increases in global warming potential from the wetland. Our study provides insights into how climate change and human acitivies affect greenhouse gas emissions from alpine wetlands, and they suggest that water table management may be effective at mitigating future increases in emissions.

INTRODUCTION

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are three major greenhouse gases (GHGs) that contribute to the "greenhouse effect".[1] The increasing emissions of greenhouse gases since the beginning of the industrial era have increased global mean temperature by approximately 1.0°C[1]; during this period, the concentrations of CO_2, CH_4, and N_2O have increased, respectively, approximately 0.3, 1.0, and 0.4% per year.[2] These three gases show, on a mass basis, quite different global warming potential (GWP): the GWP of CH_4 is 28 times that of CO_2, while the GWP of N_2O is 298 times that of CO_2 over a 100-year time frame.[1,3,4] Therefore, the different greenhouse gases emitted by an ecosystem need to be modeled separately in order to accurately assess the overall GWP.

While the predominant cause of the escalating concentrations of GHGs in the atmosphere stems from anthropogenic activities, it's noteworthy that approximately one-third originates from natural sources, particularly wetland soils.[2,5] Covering a mere 8% of the total land area, wetlands house a substantial 29–45% of soil organic carbon,[6,7] playing a pivotal role in the global carbon cycle and climate change.[8–10] On one hand, wetlands can exert a cooling effect on the climate by accumulating carbon in soils, where it remains stable and does not decompose due to the waterlogged conditions.[11,12] On the other hand, waterlogged wetlands have the potential to warm the climate because their low redox potential favors CH_4 production and denitrification, producing N_2O.[11,13,14] Therefore, the waterlogged condition stands out as a crucial factor in influencing GHG emissions in wetlands.[6,14–17]

In wetlands, the decomposition of organic matter is intricately linked to the availability and diffusivity of oxygen (O_2), influenced by the hydrological regime, significantly affecting GHG emissions into the atmosphere.[14,18,19] O_2 diffusion in water occurs approximately 10^4 times slower than in air.[20] Consequently, an increased water table depth (WTD) leads to a rapid increase in oxygen within wetlands, promoting aerobic decomposition of litter, and subsequently raising CO_2 emissions.[16,17,21] For instance, the CO_2 emission decreased by 31% in fens after raising water table by 20 cm.[17] But methanogenesis is predominantly governed by anaerobic conditions in wetlands.[14,22] An increase of WTD reduces soil anaerobiosis, diminishing methanogen abundance, decreasing CH_4 production, and enhancing CH_4 oxidation. Conversely, reduced WTD fosters anaerobic CH_4 production.[8,23,24] Moreover, decreased WTD creating anaerobic conditions may convert ammonium

[1]College of Geography and Remote Sensing, Hohai University, Nanjing 210098, China
[2]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[3]Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China
[4]Key Laboratory of Geographical Processes and Ecological Security in Changbai Mountains, Ministry of Education, School of Geographical Sciences, Northeast Normal University, Changchun 130024, China
[5]Institute of Environment Sciences, Department of Biology Sciences, University of Quebec at Montreal, Case Postale 8888, Succursale Centre-Ville, Montreal Quebec H3C 3P8, Canada
[6]College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[7]National Earth System Science Data Center, National Science & Technology Infrastructure of China, Beijing 100101, China
[8]School of Geography Science, Hunan Normal University, Changsha 410081, China
[9]Lead contact
*Correspondence: zhuq@hhu.edu.cn
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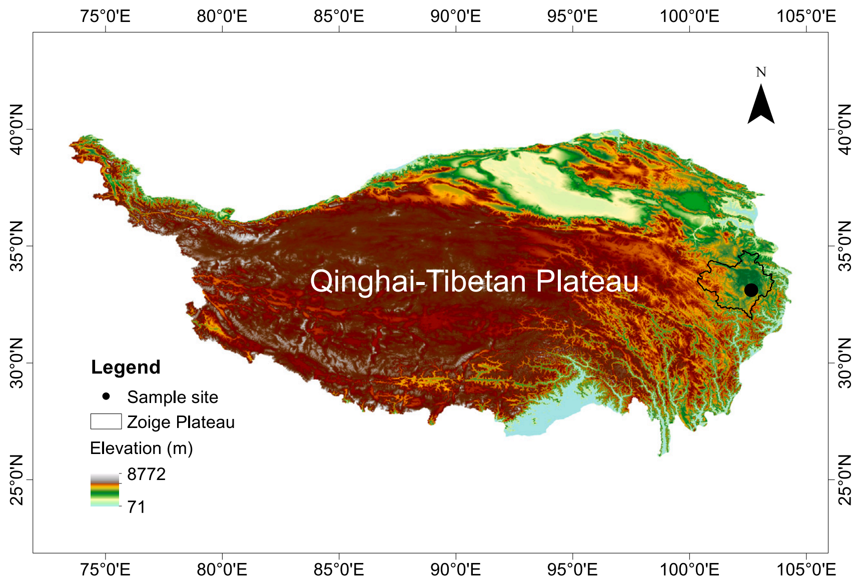

Figure 1. Location of the study site

into nitrate, further converted into the climate-warming N_2O.[4] And fluctuations of WTD have been suggested as favorable conditions for alternating nitrogen (N) oxidation and reduction processes tending to enhance N_2O emissions.[4]

Nevertheless, there remains a knowledge gap in our understanding of how changes in WTD impact the potential complexity of specific GHG emissions and their GWP,[6,25] which reflects the complexity of the underlying processes. The GWP of CH_4 and N_2O are 28 and 298 times that of CO_2 over a 100-year time frame, respectively.[1,3] Decreased WTD of wetlands may decline CO_2 emission[6] and respiration rates but may experience increased emissions of CH_4 and N_2O, potentially resulting in accelerating climate warming.[4,14] Thus, even if decreasing WTD may benefit soil carbon sequestration, which may be unfavorable from an atmospheric perspective because of the higher radiative forcing of CH_4 and N_2O.[4] Additionally, water tables in wetlands may decrease not only due to anthropogenic drainage but also intensified summer droughts.[26] Warming and extreme drought events may lead to dramatic changes of global WTD in the future.[6,27] Therefore, urgently clarifying the influence of WTD on GHG emissions is crucial in light of the rapid changes caused by climate change and human activity. These changes are altering vegetation, carbon cycling, and soil biogeochemistry in wetlands, strongly modifying their GHG emissions[4,9,28] and potentially contributing to climate feedback.[29]

The present study explored emissions of CO_2, CH_4, and N_2O from an alpine wetland ecosystem (fen) using static chambers and gas chromatography, and it analyzed how such emissions are influenced by water table. Our study site was a wetland on the Zoige Plateau (Figure 1), located on the northeast edge of the Qinghai-Tibetan Plateau in China. The wetlands in this region cover an area of 6,180 km^2, just over 30% of the entire plateau surface.[30] These wetlands substantially influence the regional GHGs budget.[31] During the past 50 years, the Zoige Plateau has experienced substantial warming and anthropogenic disturbance,[10] which has changed the WTD and consequently altered wetland structure and function.[29]

In our study, we hypothesized that managing the water table may be a way to mitigate increases in GWP due to GHG emissions from alpine wetland. To explore this possibility, we measured emissions of CH_4, N_2O, and CO_2 at a typical alpine wetland on the Qinghai-Tibetan Plateau and reasoned that larger WTD would create aerobic conditions that would accelerate organic matter decomposition, thereby decreasing CH_4 emission while stimulating CO_2 and N_2O emissions.

RESULTS

Environmental conditions during measurements

From April 2017 to April 2019, the long-term mean air temperature was 2.9°C (Figure 2A). Mean monthly air temperature showed substantial seasonal variation, ranging from −8.3°C to 13.1°C, with higher temperatures usually recorded during the growing season from May to September; temperatures were often below zero from October to April. Long-term mean precipitation was 798 mm (Figure 2B), and precipitation varied seasonally in parallel with air temperature. Precipitation fell mainly during the growing season. July 2017, in contrast, was particularly dry: precipitation was only 66.8 mm during that month. WTD over the observation period ranged from −3 to 100 cm (Figure 2C), though it tended to remain between 0 and 20 cm, except in July and August 2017.

Dynamics of greenhouse gas fluxes

The CO_2 flux showed a seasonal pattern (Figure 3A): the flux was much larger during the non-growing season than during the growing season from May to September. The CO_2 flux was negative during the growing season (except in August) indicating a net CO_2 sink function for the

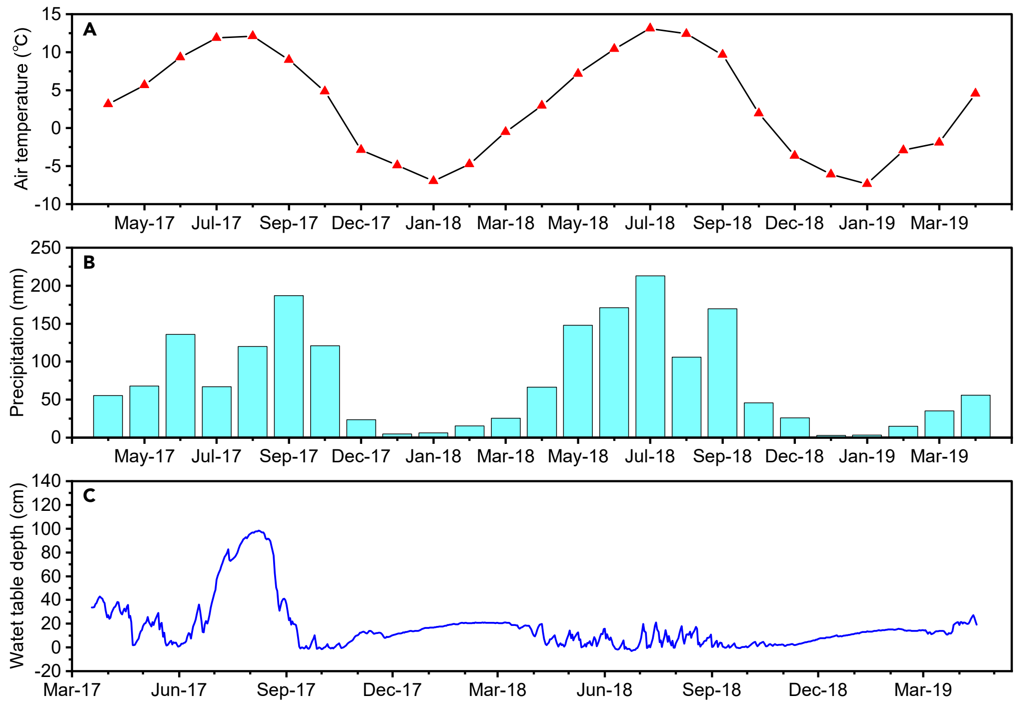

Figure 2. Environmental conditions during measurements between April 2017 and April 2019

(A) Monthly air temperature.

(B) Precipitation.

(C) Daily water table depth.

ecosystem during these measurements. The maximum net sink strength was about 4669.68 $\pm$ 66.63 mg CO_2 m^{-2} d^{-1} in July 2018. CO_2 emissions were observed during the non-growing season. Maximum CO_2 emission during the observation period was about 5015.29 $\pm$ 82.42 mg CO_2 m^{-2} d^{-1} in December 2017. Throughout the observation period, mean CH_4 flux ranged from 2.30 $\pm$ 0.23 to 173.75 $\pm$ 63.95 mg m^{-2} d^{-1}. In June 2017, CH_4 flux declined while WTD increased, and the flux was close to zero during the non-growing season (Figure 3B). Conversely, WTD fell in 2018 while CH_4 flux peaked during the growing season. N_2O flux remained low throughout the observation period (Figure 3C). The study site functioned as both a sink and source of N_2O, with flux varying from -0.46 ± 0.19 to 0.47 $\pm$ 0.06 mg m^{-2} d^{-1}. In 2017, flux was negative, indicating net absorption by the wetland. The smallest N_2O fluxes coincided with the highest WTDs. N_2O flux was close to zero during the growing season in 2018.

Relationships between WTD and greenhouse gas fluxes

Regression analysis showed positive correlation between CO_2 flux and WTD in the growing and non-growing seasons ($p < 0.05$, Figures 4A and 4B). The CO_2 flux gradually increased with increasing WTD. According to regression, the relationship between CH_4 flux and WTD was clearly nonlinear ($p < 0.01$, Figure 4C): flux was maximum when WTD was close to zero, whereas it was nearly zero when WTD exceeded 30 cm. The flux data conformed to an exponential relationship across a WTD range from -2 cm to 96 cm N_2O flux showed a quadratic relationship with WTD: flux increased up to a WTD around 35 cm, then declined thereafter ($p < 0.01$, Figure 4D).

Influence of WTD on overall GWP

Next, we considered the GWP of each gas individually and together, after appropriate weighting (see STAR methods) (Figure 5). The observed linear relationship between the GWP of CO_2 and WTD suggested that increment in WTD of 10 cm should increase CO_2 emissions by around 1.0 tCO_2-e ha^{-1} yr^{-1}. The nonlinear relationship between the GWP of CH_4 and WTD suggested that reduction in WTD from 30 cm to 0 cm should increase CH_4 emissions by approximately 15 tCO_2-e ha^{-1} yr^{-1}. The nonlinear relationship between the GWP of N_2O and WTD suggested that WTD should not substantially affect the GWP. When WTD increased more than 60 cm, the wetland turned from being an N_2O source to sink. The overall GWP first declined and then rose with increased WTD. The smallest overall GWP (7.6 tCO_2-e ha^{-1} yr^{-1}) was observed at a WTD of 18 cm.

Estimation of annual GWP of the Zoige wetland

From 2017 to 2019, the average overall GWP of the Zoige wetland was 11.72 tCO_2-e ha^{-1} yr^{-1}, based on *in situ* measurements. The maximum GWP was 15.57 tCO_2-e ha^{-1} yr^{-1} in 2019, and the minimum GWP was 7.29 tCO_2-e ha^{-1} yr^{-1} in 2017 (Figure 6A). As a complementary

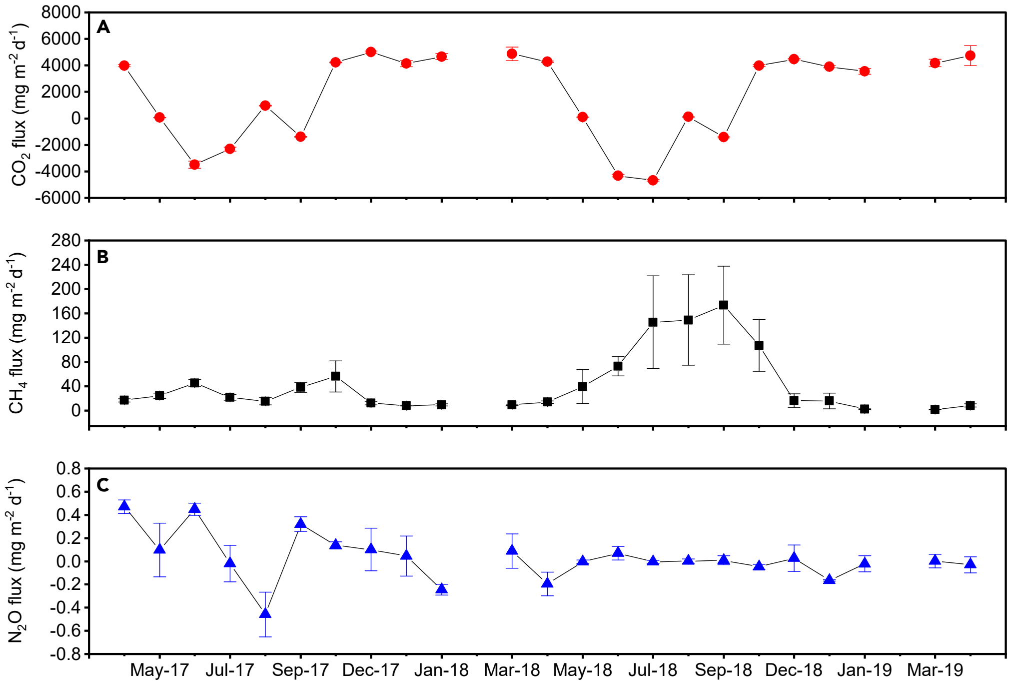

Figure 3. Greenhouse gas fluxes during measurements between April 2017 and April 2019

(A) CO_2 flux.

(B) CH_4 flux.

(C) N_2O flux. Values are the mean of replicate samples. Positive values correspond to emissions into the atmosphere. The bars represent standard deviation (SD). Measurements were not taken in February of each year (see STAR methods).

approach, we estimated GWP based on the observed relationships between WTD and greenhouse gas fluxes. In this approach, average GWP was 12.76 tCO_2-e ha^{-1} yr^{-1}, maximum GWP was 15.57 tCO_2-e ha^{-1} yr^{-1} in 2020 and minimum GWP was 10.04 tCO_2-e ha^{-1} yr^{-1} in 2017. Overall GWP in 2018 was similar between the *in situ* measurements and the modeling. In 2017, the measured GWP was lower than the corresponding estimate, whereas the converse was observed in 2019 (Figure 6A). From 2017 to 2021, the proportion of overall GWP due to CO_2 and CH_4 was much larger than the <1% due to N_2O. In 2017, CO_2 contributed about 73% to overall GWP. In 2018 and 2019, CO_2 and CH_4 contributed to similar extents to overall GWP. In 2020 and 2021, CH_4 contributed more than CO_2 (Figure 6B).

DISCUSSION

Influence of WTD on greenhouse gas fluxes

The WTD has the potential to impact soil physicochemical properties, including hydrothermal conditions, which may elucidate a portion of the variability in GHG emissions across distinct WTD.[32] Alterations in the WTD can affect the physiological properties of plants, including light utilization efficiency, photosynthesis, and respiration, consequently influencing plant growth.[33] CO_2 flux increased with increased monthly WTD (Figures 4A and 4B). In line with our findings, the correlation between elevated CO_2 emissions at greater WTD was evidenced by previous studies in Zoige wetland,[21,33,34] coastal wetland,[35,36] and tropical wetland.[37] In wetlands, the decomposition of organic matter is manipulated by O_2 availability and diffusivity as related to WTD.[14] Oxygen concentration in the soil profile could be strongly controlled by the changing WTD over time and then the level of redox potential could be changed consequently, which could affect the GHG emissions.[19,21,34,38] Flooding of wetlands enhances anaerobic conditions as air spaces in the soil fill with water, inhibiting the transport of oxygen from the soil to the rhizosphere zone and limiting aerobic microbial activity, ultimately reducing CO_2 emissions.[2,29,39] These emissions are further reduced by toxic byproducts that accumulate under anoxic conditions and limit microbial growth and activity.[36,40] Thus, decreased WTD (rewetted) can induce a decrease in CO_2 emissions and respiration rates in wetlands,[33,41] and thus help in mitigating the adverse effects of climate change.[33] For example, the CO_2 emission decreased by 31% in agricultural fens after raising the water table by 20 cm.[17] Rewetting decreased average CO_2 emissions and decreased total carbon emission by more than 40% in Zoige wetlands.[33] Even a volume equivalent to 10% of anthropogenic CO_2 emissions could be mitigated through global wetland restoration.[6] Conversely, greater WTD enhances soil aeration and promotes oxidation by helping oxygen diffuse into the deeper soil. This activates soil microbes and roots, accelerating the decomposition of soil organic matter and giving rise to CO_2.[21,25,42] At the same time, the aerobic conditions activate phenol oxidase to break down phenolic compounds in the soil that normally inhibit the hydrolytic enzymes in soil that contribute to organic matter decomposition.[32] For instance, an increase of WTD by 12 cm and 15 cm in the Zoige peatland led to respective increases of 17% and 20% in CO_2 emissions.[21]

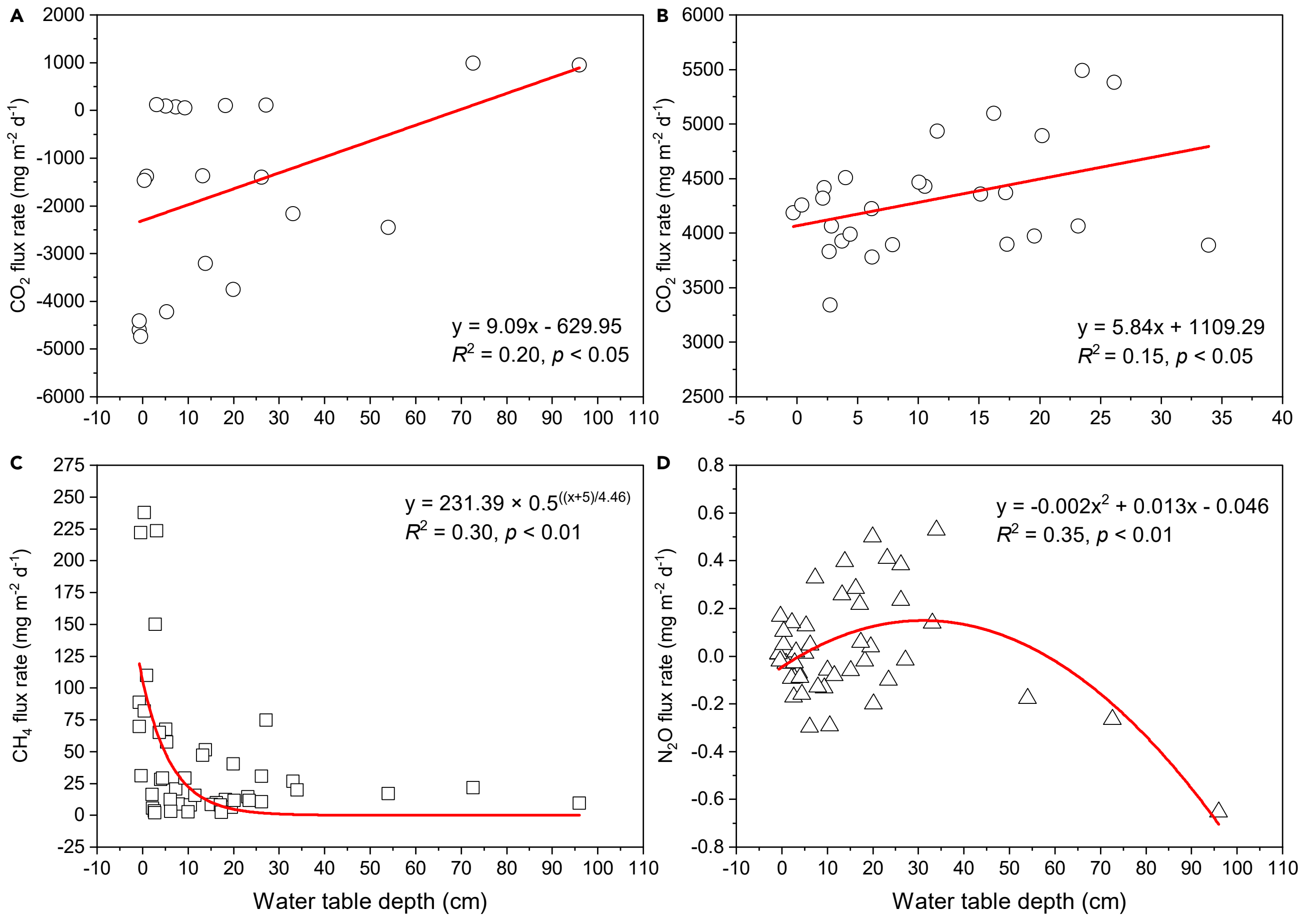

Figure 4. Relationships between water table depth (WTD) and three major greenhouse gas fluxes

Relationships between WTD and CO_2 fluxes during the (A) growing season or (B) non-growing season, (C) CH_4 flux and (D) N_2O flux. A positive sign for emissions to the atmosphere and vice versa. The relationships between CO_2 flux and WTD were fitting during growing and non-growing seasons, respectively, because of CO_2 flux was calculated from two situations (see STAR methods).

And an increase of 1–10 cm resulted in nearly a 100% increase in summer CO_2 emissions in a subalpine fen of North America.[43] Additionally, tropical peatlands turned into a source of CO_2 after artificial drainage, leading to 40–75% increases in CO_2 emissions with an increase of WTD by 40 cm.[44]

Methanogenesis in wetlands is heavily influenced by anaerobic conditions,[14,17] making CH_4 emission highly responsive to changes in hydrological conditions.[24] WTD is the main abiotic factor affecting CH_4 flux in wetlands.[17,30,45] Our data identify the exponential relationship between CH_4 emissions and WTD (Figure 4C). These results are consistent with the fact that the WTD determines the degree of aerobic and anaerobic metabolism in wetland sediments,[31,45] which in turn influences CH_4 production and oxidation.[26,29] In our experiments, CH_4 emissions were higher when the WTD was close to or above the soil surface, reflecting the fact that anaerobic conditions decrease the diffusion of oxygen, whereas when the WTD was below 30 cm, oxygen could diffuse more easily into the soil and promote microbial aerobic CH_4 oxidation.[6,7,34,36] Elevated WTD contributes to a decline in CH_4 emissions by diminishing the abundance of methanogens, reducing CH_4 production, and enhancing CH_4 oxidation.[6,11,14,42] Conversely, reduced WTD poses a greater potential for anaerobic CH_4 production.[8,13,23,26,30] Thus, shallow standing water or flooding can make wetland an evident CH_4 source, and potentially accelerate global warming.[4] The correlation between CH_4 emission and wetland's WTD remains consistent across various regions, as confirmed by both field observations and manipulation experiments.[3,23,26,29,33,46–48] For example, WTD negatively correlated to CH_4 emissions, and rewetting increased CH_4 emissions of wetland on the Qinghai-Tibetan Plateau[33,47,48]; On the global scale, when the water table was close to or above the soil surface (about 5 cm), wetland soils as a whole experience water-saturated anaerobic conditions,[6] which promoted the production and release of CH_4.[6,16,25] In addition, methane transport within plants, particularly through the vascular system,[49] is influenced by the water content of the soil. Adequate water table enables the vascular system to efficiently transport methane within the plant,[50] resulting in an increase of CH_4 emissions.

Generally, quantifying N_2O flux can be challenging due to its relatively small magnitudes.[51] N_2O flux at our study site did not vary seasonally, with small values (Figure 2D). The flux was both positive and negative at different times during the observation period, indicating that the

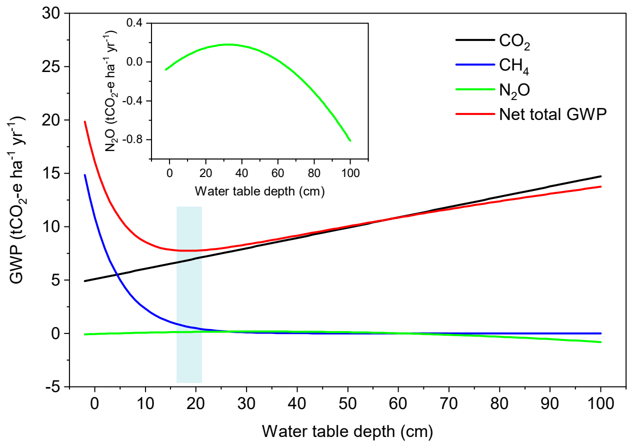

Figure 5. Global warming potential (GWP) due to emissions of three major greenhouse gases at the study site

The overall GWP, calculated by summing the weighted GWPs for the three gases (see STAR methods), is shown in red. The *inset* shows a more detailed view of the N_2O flux as a function of water table depth.

Zoige wetland can function as N_2O source or sink.[31,52,53] N_2O is produced by the collaboration of nitrification and denitrification in soil.[3] Alternating oxic and anoxic conditions in wetlands can promote N_2O production and emission.[31,54] But soils also can take up N_2O from the atmosphere,[55,56] and this has been reported in natural wetlands.[4,52,57] In wetlands, fluctuations in the water table may mediate ammonium nitrification (accumulation under anaerobic conditions), producing nitrate that acts as an electron acceptor for denitrifiers and thus may stimulate N_2O production from nitrification and denitrification.[4] However, when nitrate is depleted, N_2O reductase synthesized for denitrification may be abundant, thus mediating microbial use of atmospheric N_2O as an electron acceptor.[55,58] This may explain the functions of wetland as N_2O source or sink. But the factors (microbial denitrification, pH conditions, N oxidation and so on) affecting N_2O emissions are more complex.[4] Further work should be done to explore the influence of those factors on N_2O emissions in Zoige wetlands.

Furthermore, alterations in WTD may impact vegetation composition and production in wetlands.[14] The makeup of vegetation is also crucial for gas exchange, given the distinct capacities of functional types to capture and transport carbon.[59,60] But the mechanisms driving species shifts due to short-term changes in the WTD are still poorly understood. For example, sedge production (the dominant vegetation type in the study area) has no consistent response pattern to WTD alteration.[14] Therefore, further research is needed to understand the impact of vegetation succession resulting from changes in WTD on GHG emissions in wetlands.

Influence of WTD on overall GWP

WTD affects the net warming impact of GHGs.[2,6,9,15,29] Previous studies have shown that a small change in the wetland WTD may have profound impacts on the relative importance of GHGs in terms of overall C emissions.[6,16,25] On the global scale, Huang et al. (2021) found that the sensitivities of GHG fluxes of peatland to the magnitude of water table drawdown were 4.1 mg CO_2 m^{-2} h^{-1} for CO_2 and -2.9 mg CO_2-eq m^{-2} h^{-1} for CH_4 per 1 cm water table drawdown, respectively.[25] Moreover, Evans et al. (2021) discovered that a reduction of 10 cm in WTD could lead to a decrease in the combined warming effect of CO_2 and CH_4 emissions by at least 3 tCO_2 ha^{-1} yr^{-1}, up to a WTD of less than 30 cm.[16] And WTD within 10∼30 cm of the soil surface can even have a net cooling effect in wetlands.[16] We did not observe a cooling effect at our study site, but the smallest overall GWP at our study was 7.6 tCO_2-e ha^{-1} yr^{-1} for a WTD of 18 cm (Figure 5). Although, increasing WTD reduced CH_4 emissions and increased wetland CO_2 emission, the increment in CO_2 emissions outweighs the climate benefits of reduced CH_4 in terms of global warming potential,[25] which still had a warming effect in Zoige wetland (Figure 5). This aligns with prior research, indicating that drained wetlands typically exhibit a heightened GWP,[15] even with diminished CH_4 emissions, owing to an upsurge in CO_2 emissions.[61,62] In contrast, the GWP tends to be lower after rewetting, primarily because the augmented CO_2 uptake surpasses the concurrent rise in CH_4 emissions, particularly over an extended period.[11,33] Since WTD fluctuations can accelerate the release of labile soil carbon into the atmosphere,[3,36] we suggest that maintaining a relatively constant WTD (about 18 cm) may promote soil carbon sequestration and reduce GHG emissions from alpine wetlands. This finding may have important implications for wetland construction and restoration on the Qinghai-Tibetan Plateau.

Annual GWP in the Zoige wetland

The alpine wetlands of Tibetan Plateau have a positive net GWP,[9] and consistent with this, *in situ* measurements during our observation period from 2017 to 2019 indicated an average GWP of 11.72 tCO_2-e ha^{-1} yr^{-1} on the Zoige wetland (Figure 6A). Our comparison of measured annual GWP with values estimated from daily WTD suggests that the lack of measured data during the non-growing season may have led to an underestimation of measured GHG emissions in 2017, while the lack of data from the growing season may have led to an overestimation of emissions in 2019. Altogether, our analysis suggests that the GWP of the entire region of Zoige wetland can be roughly estimated from the WTD. From 2020 to 2021, the WTD at our study site was usually shallower than the optimal 18 cm, leading to larger GWP. The overall GWP at

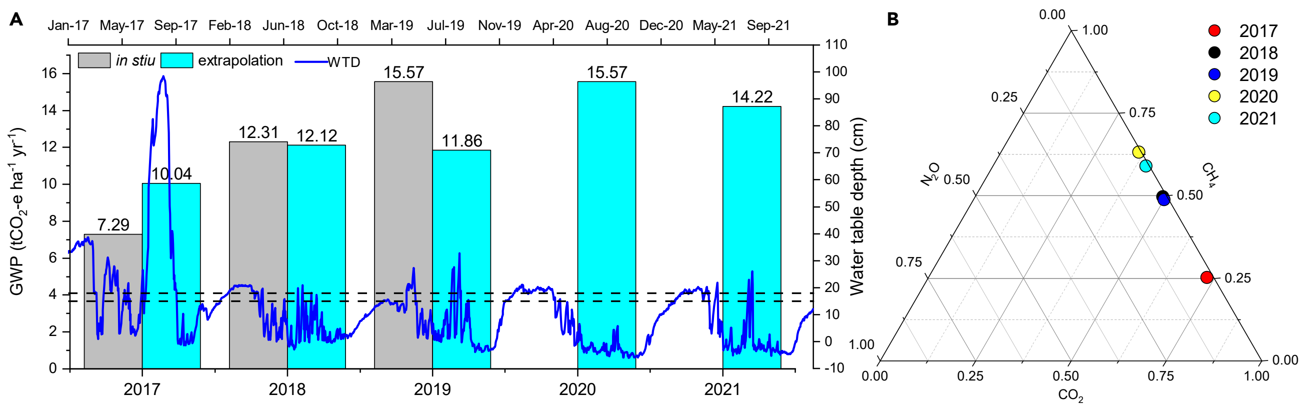

Figure 6. Annual global warming potential (GWP) of the Zoige wetland from 2017 to 2021

(A) Annual GWP from *in situ* measurements (gray bars), or estimated from the models based on water table depth shown in Figure 3 (cyan bars). The left axis plots GWP; the right axis, water table depth (WTD). The continuous blue line shows daily water table depth, while the black dashed line indicates a depth of 18 cm.
(B) Ternary diagram showing the relative annual contributions of the three greenhouse gases to overall GWP of the Zoige wetland in each year, based on the extrapolation method.

our study site was due primarily to CO_2 and CH_4 since N_2O contributed <1% to the total GWP (Figure 6B), consistent with the dominant effect of CO_2 and CH_4 reported for other wetlands.[3] We suggest that N_2O emissions from wetlands on Qinghai-Tibetan Plateau contribute negligibly to global warming, consistent with the previous reports from Marín-Muniz et al. (2015)[2] and Kandel et al. (2018).[4]

Under inundated conditions, soil respiration declines, which reduces CO_2 emissions, yet CH_4 emissions increase,[3,7] which may help explain the GWP at our study site in 2020 (Figure 6). In 2017, WTD at our site fluctuated from −5 to 100 cm and decreased CH_4 emissions, which may reflect inhibition of CH_4 production, stimulation of CH_4 oxidation, or both.[10,29,36] Nevertheless, greater CO_2 flux with greater WTD outweighed the GWP benefits of reduced CH_4, ensuring that our wetland maintained a net warming impact (Figure 6). The conditions and processes that we analyzed at our study site are likely to intensify in the future. Climate models continue to project warming,[1] which will degrade permafrost and promote evapotranspiration in the Qinghai-Tibetan Plateau.[9,63] These two phenomena, together with the projected increase in rainfall on wetlands,[22,31] threaten to make the WTD fluctuate substantially. While permafrost degradation and increased rainfall may decrease the WTD, high evapotranspiration may increase it. These uncertainties in WTD fluctuations may accelerate the release of labile soil carbon in wetlands, promoting GHG emissions.[3,29,31] As part of international efforts to preserve and manage wetlands,[7,25] it may be helpful to integrate management of the WTD as a way to mitigate future increases in GWP.

Limitations of the study

Although the wetlands had the smallest GWP when the WTD was maintained at 18 cm, the finding may be applicable exclusively to wetlands of the Qinghai-Tibetan Plateau, due to the unique climatic conditions, vegetation, and wetland types. In addition, we simply assumed $NEE_{daytime}$ equal to ER during non-growing season, which could bring some uncertainties in the estimation of NEE and overall GWP. Therefore, more studies should be conducted in the future to make the regional extrapolation more reliable.

Conclusion

Our study suggests that the alpine wetlands on the Zoige Plateau exert a positive net GWP of around 11.72 tCO_2-e ha^{-1} yr^{-1}, nearly all of which is due to emissions of CO_2 and CH_4. Maintaining a suitable WTD, which at our study site appeared to be 18 cm, may help mitigate future increases in GWP due to GHG emissions on the Qinghai-Tibetan Plateau. WTD showed a positive linear relationship with CO_2 flux, but an exponential relationship with CH_4 flux. Greater WTD on Zoige alpine wetlands was associated with greater CO_2 emissions but smaller CH_4 emissions. Our findings on the importance of WTD for managing GHG emissions may help guide efforts to construct and restore wetlands on Qinghai-Tibetan Plateau.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.108856.

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AUTHOR CONTRIBUTIONS

Conceptualization, Q.A.Z and H.C.; Methodology, Q.A.Z., H.C., M.W., and J.Z.; Investigation, J.Z, X.W.L., L.W., and D.X.Y.; Writing – original draft, J.Z.; Writing – review and editing, Q.A.Z., H.C., M.W., X.W.L., and C.H.P.; Funding acquisition, Q.A.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Air temperature and precipitation	China Meteorological Data Service Center	http://data.cma.cn/
Software and algorithms		
R, used for data analysis	R Foundation for Statistical Computing	https://www.R-project.org
OriginPro 2021 (Learning Edition), used for data analysis and preparing graphs	Commercially Available Software	https://www.originlab.com/
Microsoft Excel, used for data analysis and preparing graphs	Commercially Available Software	N/A

RESOURCE AVAILABILITY

Lead contact

Further information and requests can be directed to Dr. Qiuan Zhu (zhuq@hhu.edu.cn).

Materials availability

This study did not generate new physical materials.

Data and code availability

All data reported in this paper will be shared by the lead contact upon reasonable request. Software and datasets are listed in the key resources table and method details.

The article does not report any new code.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Study site

The Riganqiao fen (33°06′ 15.419″ N, 102°39′ 05.278″ E) is located in the Zoige peatlands at an altitude of 3460 m above sea level (Figure 1).[22,64] The fen exhibits a peat thickness ranging from 4 to 10 m,[65] an average pH of 6.6–7.0, and the carbon accumulation rate ranging from 5 to 48 g m^{-2} yr^{-1}.[64,66] This region belongs to the cold Qinghai-Tibetan climatic zone. During the past decades, this region has experienced universal and significant warming, with temperature increasing by 0.04 °C yr^{-1} since 1970.[22] Accompanied with rising temperature, precipitation has decreased by 2.2 mm yr^{-1}.[10] The snow season spans from November to May, with an average snow depth of approximately 20 cm. Even in the coldest month of January, the snow cover typically persists for no more than four days.[67] During the study period of 2017–2019, the annual mean air temperature was 2.9°C, with the maximum 10.8°C in July and the minimum −10.6°C in January; precipitation was concentrated in growing seasons (May-September), with the maximum 210 mm in July and the minimum 10 mm in January (Figure 2), based on data from the China Meteorological Data Service Center (http://data.cma.cn/). The dominant plants at the site are *Carex muliensis, Scirpus triqueter, Carex meyeriana, Trollius farreri, Gentiana leucomelaena*, and *Caltha palustris*, with no moss species being present.[10,66–68]

Sampling and measurements of greenhouse gas fluxes

Fluxes of CO_2, CH_4 and N_2O were measured monthly from April 2017 to April 2019 using static chambers and gas chromatography. Sampling was scheduled from 10 a.m. to 2 p.m. in the mid-month period. No measurements were taken in February because weather conditions blocked the access to the sample site. At the sampling site, a total of eight static boxes are arranged, among which four are in a group. The bottomless static chambers (50 × 50 × 50 cm) were placed onto square collars that were permanently embedded into soil surfaces at a depth of 10 cm. The square collar was filled with water to seal the compartments from outside air. Before the collection, the static chambers will be settled for 5 min, so that the gas inside the static chamber is in a relatively stable state. Four air samples from each chamber were taken at 10-min intervals after enclosure. Each sample was sealed in separate air-tight 10-mL vacuum vials. During air sampling, temperatures were recorded by sensors positioned on the inside and outside of the chamber and connected to an electronic thermometer. Samples were transported to a laboratory, typically within one week of collection, and analyzed for GHGs using gas chromatography (7890A system, Agilent Technologies, Santa Clara, California, USA). Flux of each gas was calculated as

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

where F is gas flux; H, the chamber height (cm) above the soil surface; M, the molar mass of the gas; P, atmospheric pressure at the sampling site; V_0, P_0 and T_0, molar volume (22.4 L mol^{-1}), atmospheric pressure (101.325 kPa) and absolute temperature (273.15 K) under standard conditions; T, absolute temperature at the time of sampling; and dc/dt, the rate of change in the gas concentration.[22,68] For each chamber measurement, gas sample concentrations were plotted as a function of sampling time. Linear regressions were performed on each flux rate to verify its linearity.

Measurement of WTD and soil temperature

Water table depth (WTD), measured as a positive distance below the surface (with negative values indicating pond formation above the wetland surface), was automatically recorded at 1-h intervals from January 2017 to December 2021 using sensors (CS451, Campbell Scientific, Logan, State of Utah, USA), and then corrected to the distance from the wetland surface. During air sampling, soil temperatures were recorded at a depth of 5 cm using a digital thermometer (WatchDog-B101, Spectrum Technologies, Chicago, Illinois, USA).

Estimation of net ecosystem exchange

CO_2 flux was measured using the static chamber method and defined as the total ecosystem respiration from plants and soil during the day. In order to calculate GWP and C balance from fluxes of CO_2, CH_4 and N_2O, we estimated net ecosystem CO_2 exchange (NEE) as follows. CO_2 fluxes were partitioned into light-dependent gross primary productivity (GPP) and light-independent ecosystem respiration (ER). NEE was calculated as ER + GPP, where the sign of ER was positive and the sign of GPP was negative. As a result, NEE was positive when there was net flux of CO_2 into the atmosphere.[4] NEE included $NEE_{daytime}$ and $NEE_{nighttime}$; the latter was nearly equal to ER under the dark condition. During the growing season from May to September, $NEE_{daytime}$ was calculated as ER + GPP. During the non-growing season from October to April, vegetation at the study site underwent complete withering or shedding, and the plants were supposed to remain dormant in terms of photosynthesis during the non-growing season. Therefore, $NEE_{daytime}$ was assumed to equal ER during this period. We did not collect samples at night; instead, we used NEE (NEE_{ec}) and corresponding soil temperature data that had been collected every half hour at the same study site from September 2016 to December 2017 using the eddy covariance method.[67] The relationship between NEE_{ec} and soil temperature at night was fitted using an exponential function (Equation 2; Figure S1).[67,69] In this way, we estimated $NEE_{nigthtime}$ by combining the formula (Equation 2) with soil temperature at night during the sampling period.

$$NEE_{nighttime} = a \times exp^{(bT)} \quad \text{(Equation 2)}$$

In the function, *a* and *b* are the values estimated parameters and T is the soil temperature measured at 5 cm depth.

Monthly GPP and the ratio of GPP to $NEE_{daytime}$ were calculated using NEE_{ec} data from the eddy covariance method from September 2016 to December 2017 in our pervious study.[67] Then, the missing monthly ratio of GPP to $NEE_{daytime}$ for 2018 was replaced by the average value for the same months from 2016 to 2017. Last, we estimated $NEE_{daytime}$ during the whole measurement period using ER and the ratio of GPP to $NEE_{daytime}$ (Table S1) and obtained the value of NEE from 2017 to 2019.

Calculation of GWP

We assessed the climate impact of GHG emissions in terms of GWP, defined as time-integrated radiative forcing. Annual GHG emissions were equal to the average monthly emission rate multiplied by the number of days. Then we calculated the 100-year GWP (Equation 3) in terms of CO_2 equivalents (CO_2-e) by summing the GWP of CO_2, CH_4 (multiplied by 28) and N_2O (multiplied by 298).[1,3]

$$GWP = CO_2 + 28 \times CH_4 + 298 \times N_2O \quad \text{(Equation 3)}$$

Where CO_2 is substituted by NEE. Units for all terms are tCO_2-e ha^{-1} yr^{-1}; the weights 28 and 298 are GWP for CH_4 and N_2O to CO_2-e by weights on a 100-year perspective with feedbacks considered,[6] respectively.

QUANTIFICATION AND STATISTICAL ANALYSIS

Measurements from replicate samples were averaged to obtain mean fluxes of GHGs, while WTD was calculated by averaging daily data. We assessed the relationships between CO_2 flux and WTD using linear regression (Equation 4) during growing (May-September) and non-growing (January-April and October-December) seasons, respectively, because of estimated CO_2 flux from two situations. An exponential function (Equation 5) was applied to fit the nonlinear relationship between WTD and CH_4 flux,[16] while a polynomial function (Equation 6) was applied to fit the relationship between WTD and N_2O flux.[70] We presented only the results from the regression models showing the best fit. The Shapiro-Wilk test was employed to evaluate the normal distribution of data. In linear or non-linear regression analysis, the R^2 measured the goodness-of-fit of the regression model, while the p value (< 0.05) was utilized to assess the statistical significance of the model.

$$NEE = a \times WTD + b \quad \text{(Equation 4)}$$

$$CH_4 = a \times 0.5^{\frac{(WTD+5)}{b}} \quad \text{(Equation 5)}$$

$$N_2O = a \times WTD^2 + b \times WTD + c \quad \text{(Equation 6)}$$

Where NEE, CH_4, N_2O are the greenhouse gas fluxes, respectively; WTD indicates water table depth; a, b and c are parameters. The forms of the function are derived from Evans et al. (2021).[16]