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More Enhanced Non-growing Season Methane Exchanges under Warming on the Qinghai-Tibetan Plateau

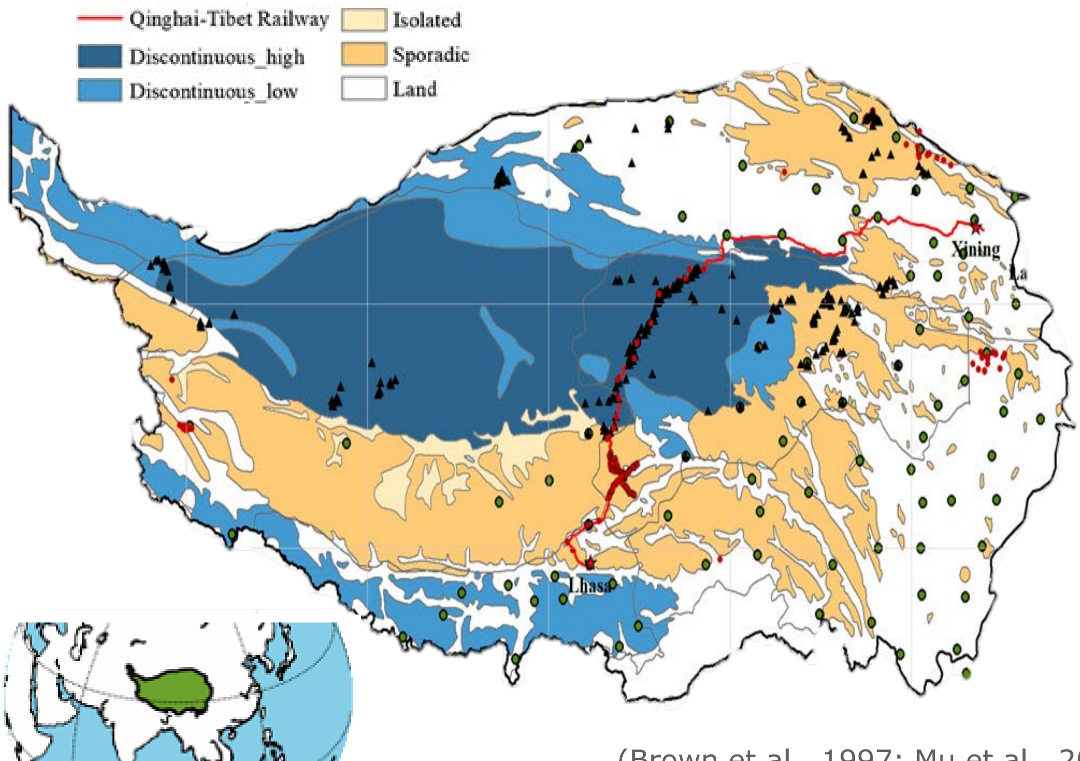
Zhenhai Liu (PhD candidate)

Prof. Shaoqiang Wang (Supervisor)

Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences

The largest area of alpine permafrost in the world

the ground that remains below 0 ◦C for at least two consecutive years.



(Brown et al., 1997; Mu et al., 2015)

Permafrost underlies approximately

40.2%

Seasonal frozen soil underlies approximately

56.0%

on the QTP

QTP permafrost zone contains about

28 Pg

of carbon

2 x

as much carbon as the atmosphere

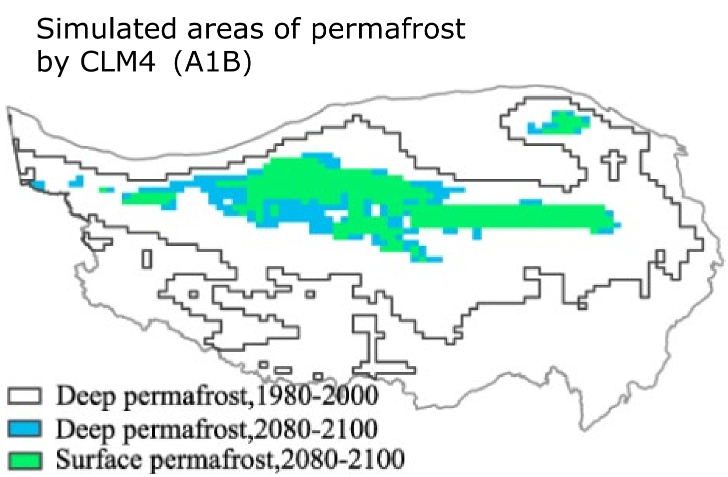
3 x

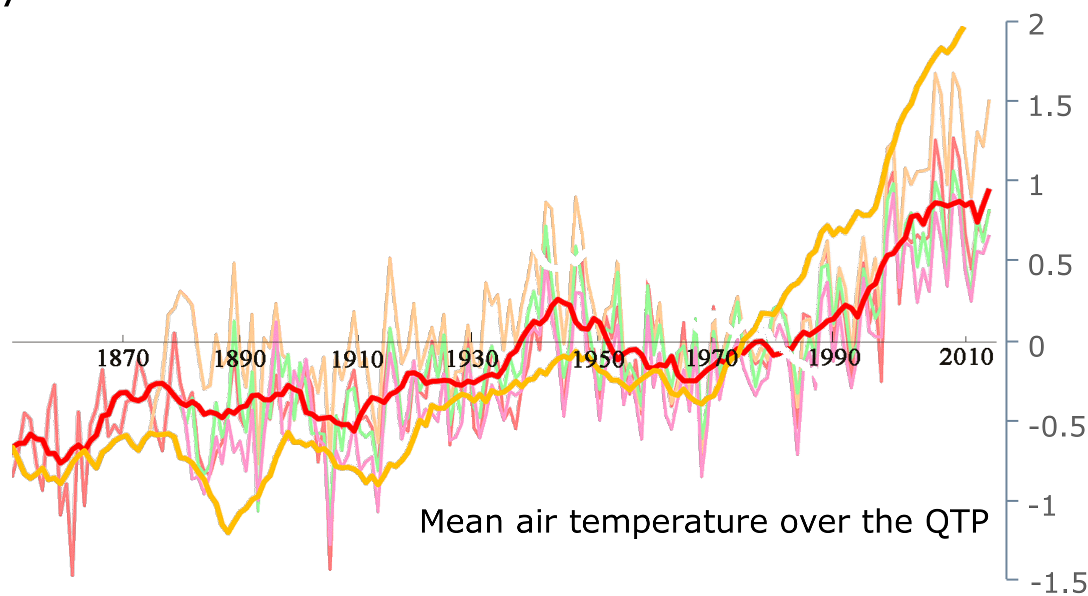
more than is in the terrestrial vegetation

Carbon pool

The degradation of permafrost

- **Accelerated warming: ~0.3 °C decade^{-1}** from 1960s, faster than the global mean (0.05-0.08 °C decade^{-1}).
- **Continuous degradation: 6.6×10^4 km^2 decade^{-1}** from 1980s on the QTP.
- **Future reduction: 81%** for the cumulative reduction of the permafrost area in medium emission scenario (A1B) by 2100.





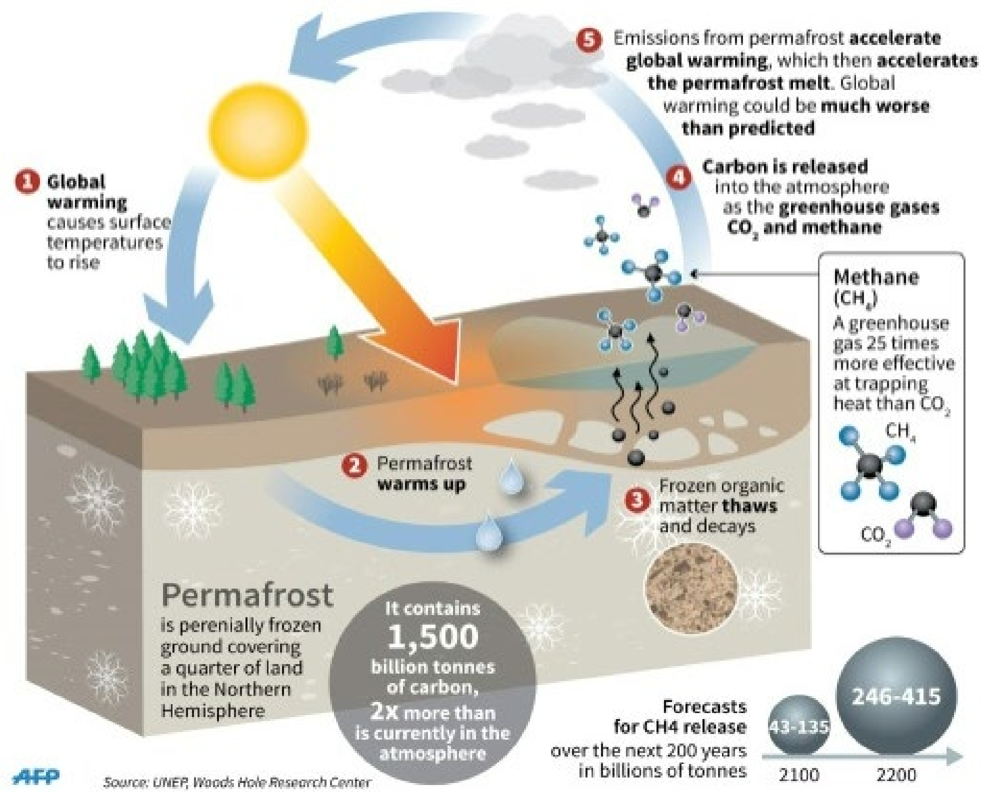
(Chen et al. 2013; Jia et al. 2020)

Timebomb

When permafrost thaws it releases carbon into the atmosphere in the form of

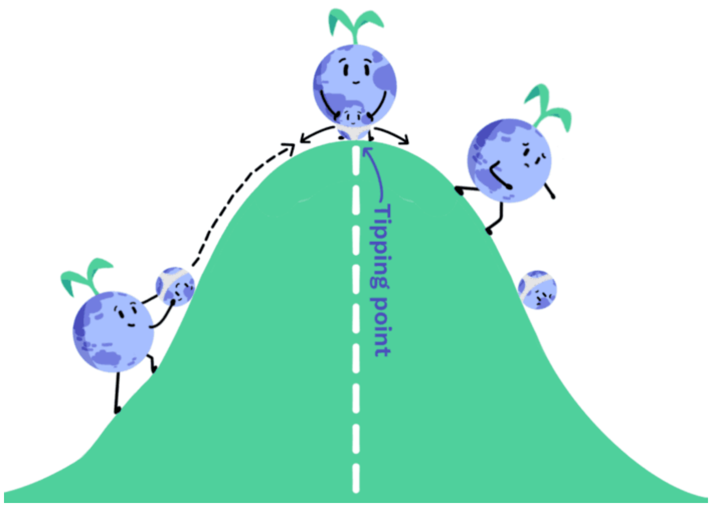
Carbon Dioxide (CO_2) and Methane (CH_4).

These greenhouse gases accelerate global warming, which then speeds up the permafrost thaw.



Tipping point

would lead to uncontrolled climate change



Methane budget

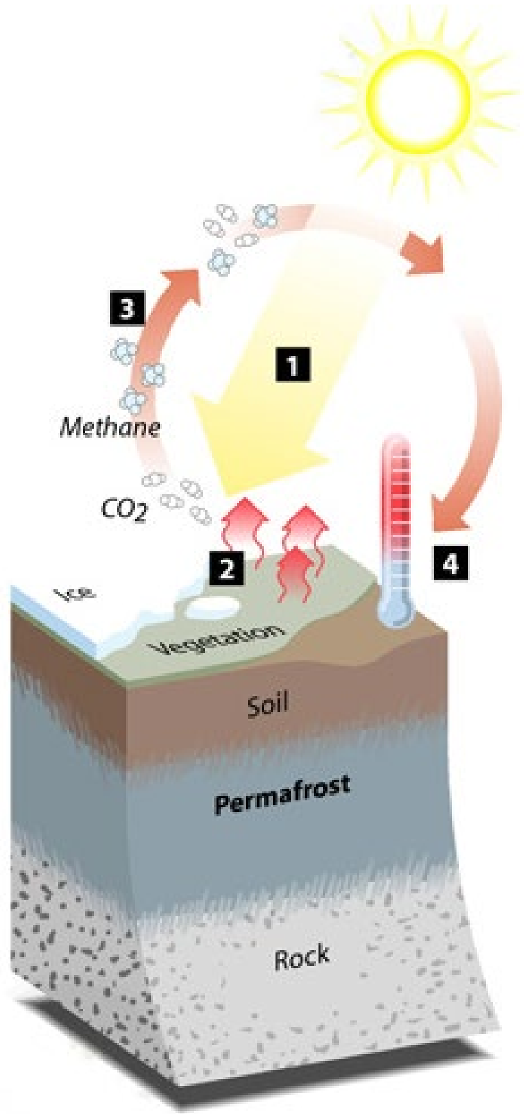
Alpine wetlands
~36% of China's natural wetlands area
fen, marshes, and peatlands
0.16-2.37 Tg C yr^{-1}
Methane source

Alpine grassland
~40% of China's grassland area
steppes and meadows
-0.55-0.10 Tg C yr^{-1}
Methane sink

?

The methane budget of wetland and grassland on the QTP are still uncertain!

Increasing uncertainty of CH_4 budget



(Wang, et al., 2020, *Science Advances*)

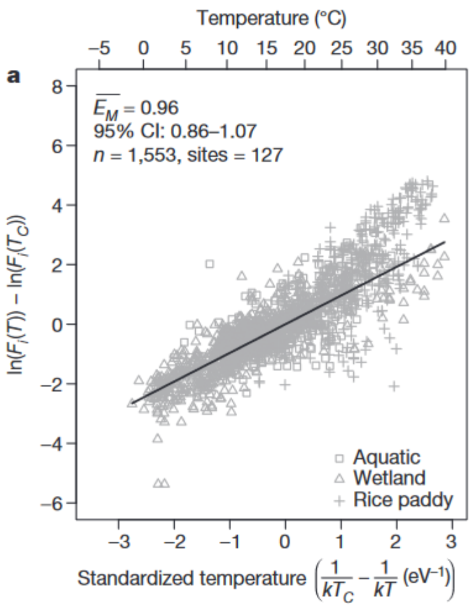
Climate warming

- Under RCP4.5 and RCP8.5 scenarios, the carbon release in permafrost area of QTP at 2100 is **~1.86±0.49 Pg** and **~3.80±0.76 Pg**, respectively.

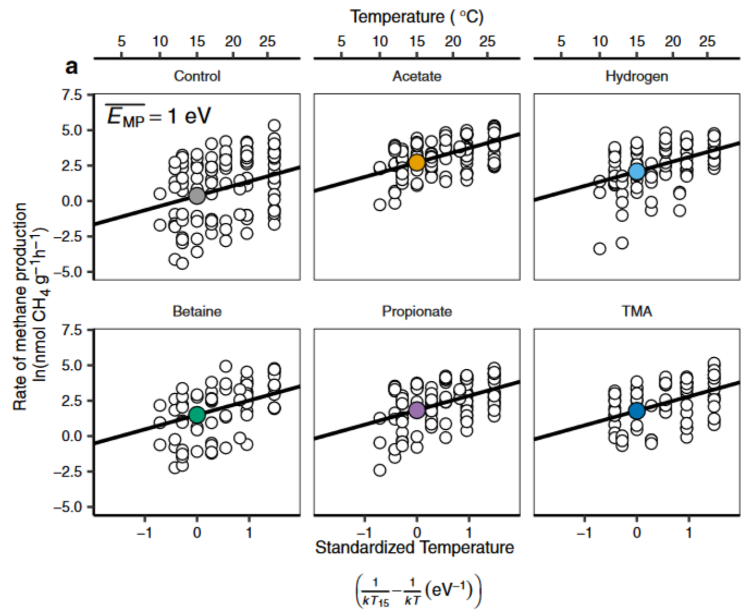
Permafrost degradation

- Wetlands and grasslands on the QTP both experiencing continued shrinkage or expansion propelled by rapid climate change and permafrost thaw.

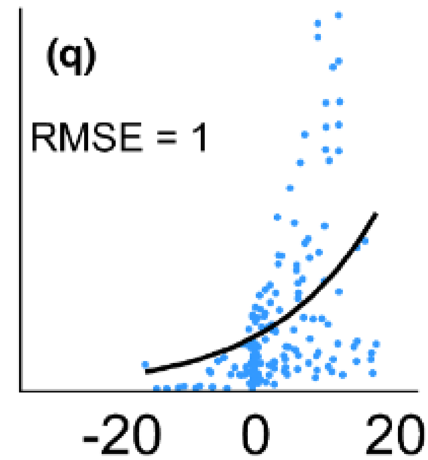
CH_4 emissions increasing as warming



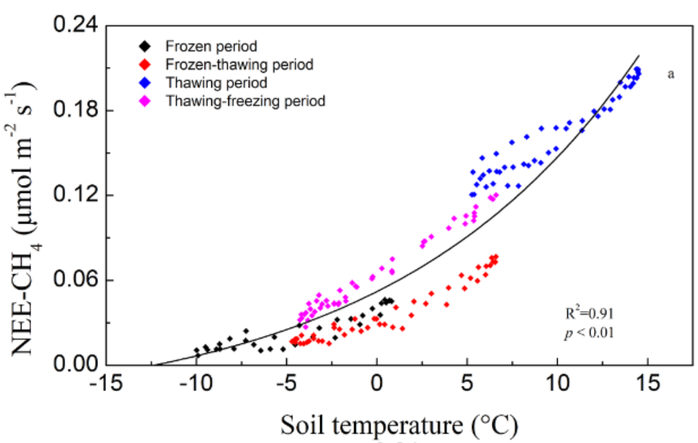
(Yvon-Durocher et al., 2014, *Nature*)



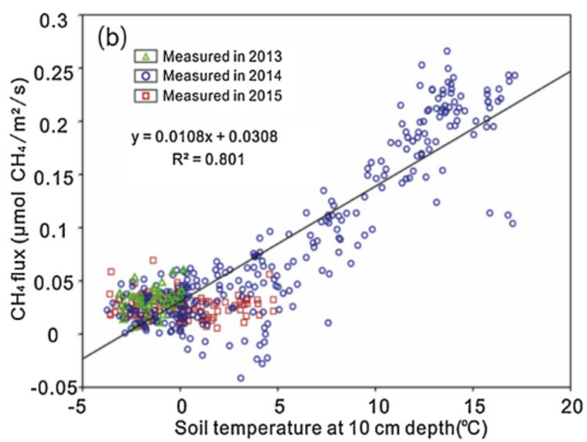
(Zhu et al., 2022, *Nat Commun*)



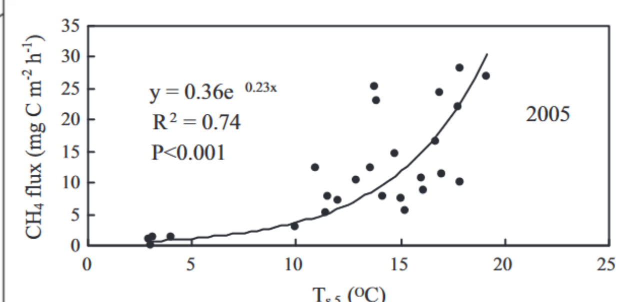
(Watts et al., 2023, GCB)



(Chen et al., 2021, *AFM*)



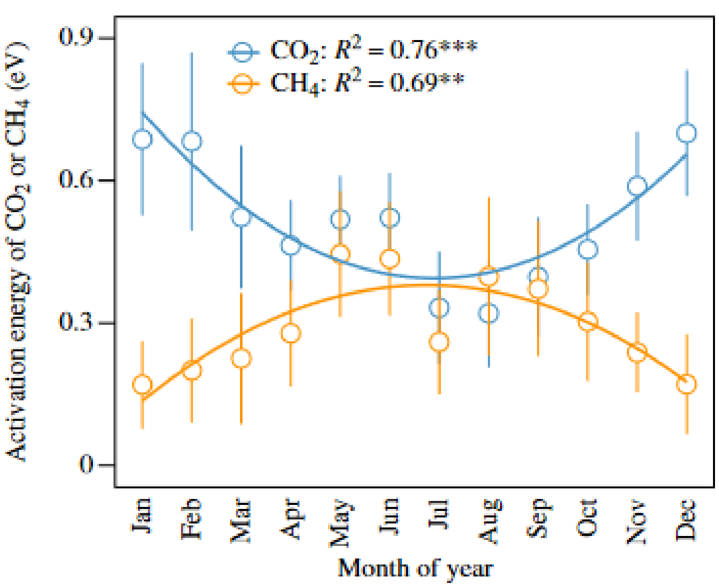
(Peng et al., 2019, *AFM*)

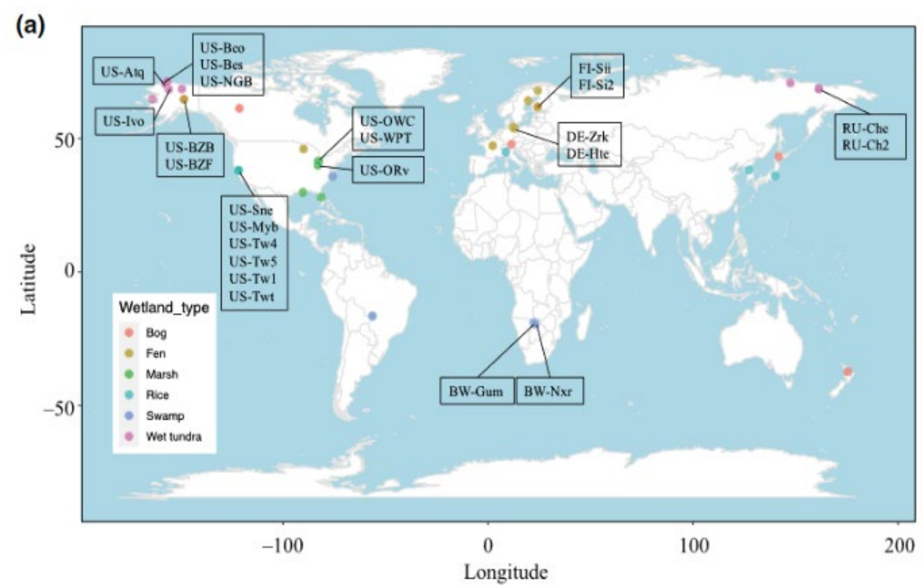


(Song et al., 2011, *AFM*)

Seasonality of global CH_4 response to warming

- Research based on global measurements shows that **the sensitivity of CH_4 emission from wetlands is correlated with soil temperatures**, and reach the maximum in summer.
- This study is based on FLUXNET database, but **lacking the measurements on the QTP**.



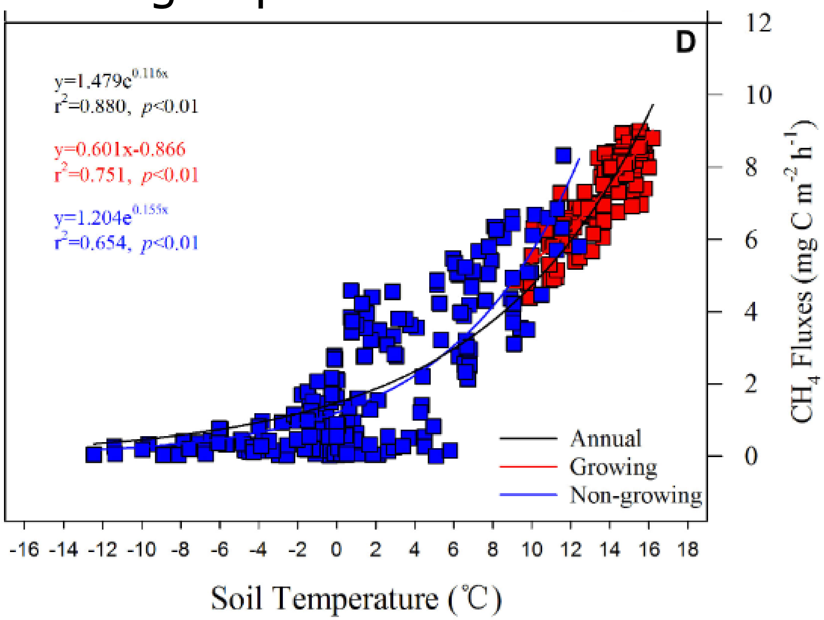


(Li et al., 2023, *GCB*)

Seasonality of CH_4 response to warming on the QTP

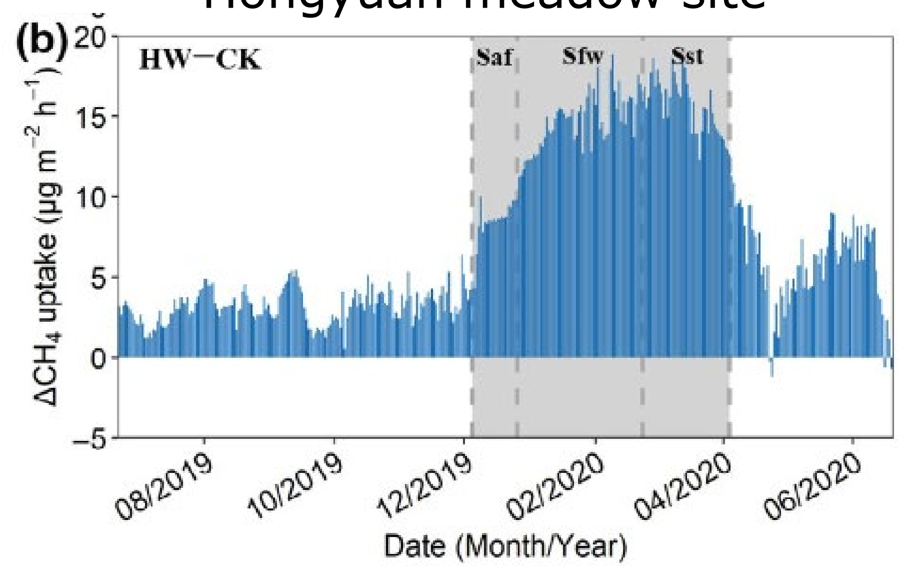
- **The warming response of CH_4 exchange in winter and spring was greater than that in summer and autumn.**

Riganqiao wetland site



(Zhang et al., 2020, *Frontiers in Earth Science*)

Hongyuan meadow site



(Peiyan Wang et al., 2020, *GCB*)

We suspect that seasonality of CH_4 response to warming on the QTP differs from that from global measurements.

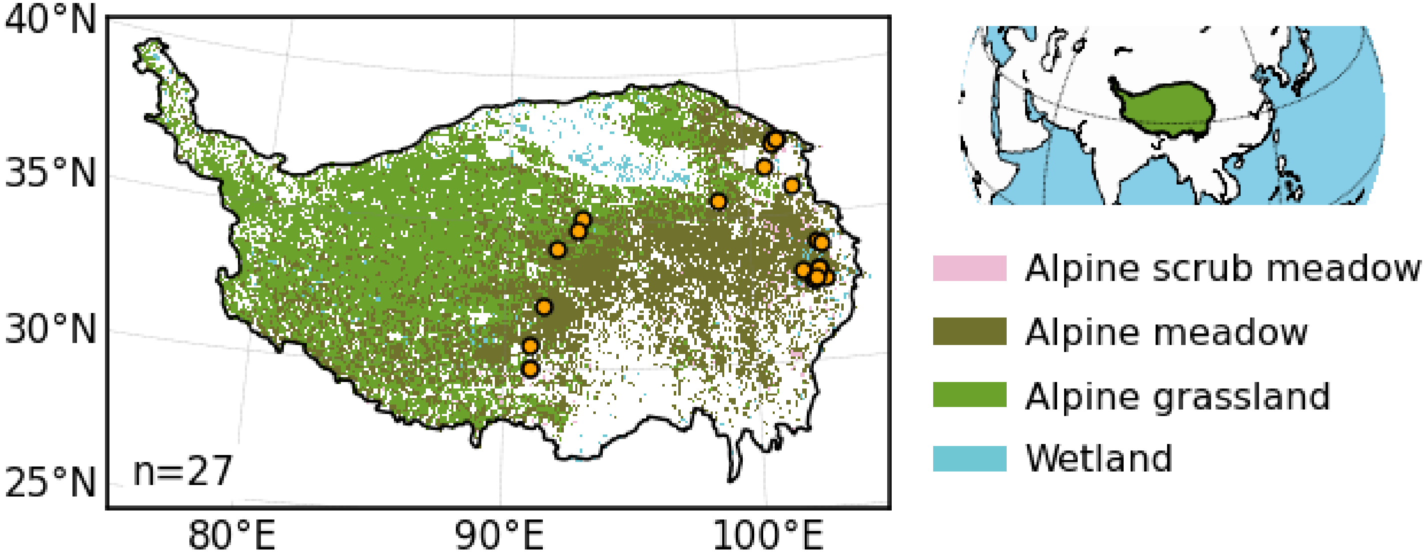
Questions

- What is the general pattern of seasonal temperature dependencies of wetland and grassland CH_4 fluxes on the QTP?
- How does the seasonality affect CH_4 source/sink in wetlands and grasslands on the QTP with soil warming?

Meta analysis

11 wetland sites, 16 grassland sites

9,745 daily observations



Variations of CH_4 fluxes with Ts

① Soil temperature-CH4 fitting

② Temperature dependent calculation

Warming impacts on CH_4 exchange

③ Control experiment

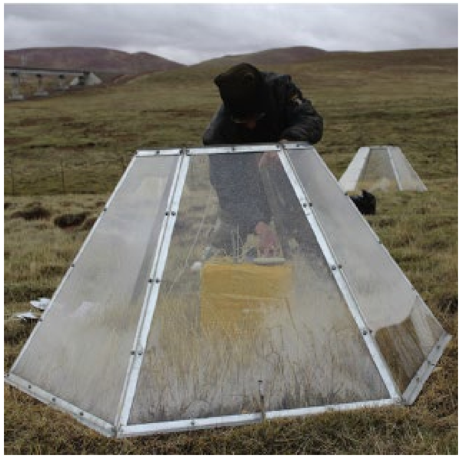
④ Machine learning modeling

Data collection

Manual Static Chamber (MSC)

17 sites

once per day, once per week, or once per month



Continuous Automated Chamber (CAC)

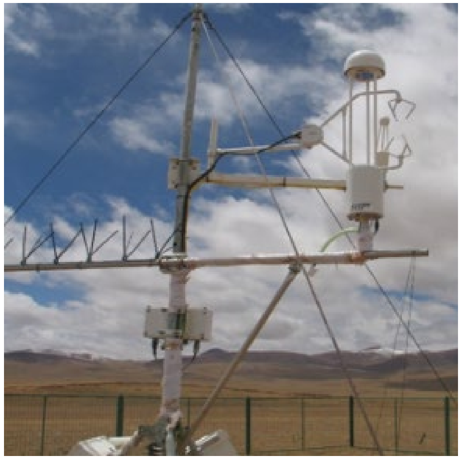
2 sites

Once per 30 minutes or every per hour

Eddy Covariance (EC)

8 sites

Once per 30 minutes or every per hour

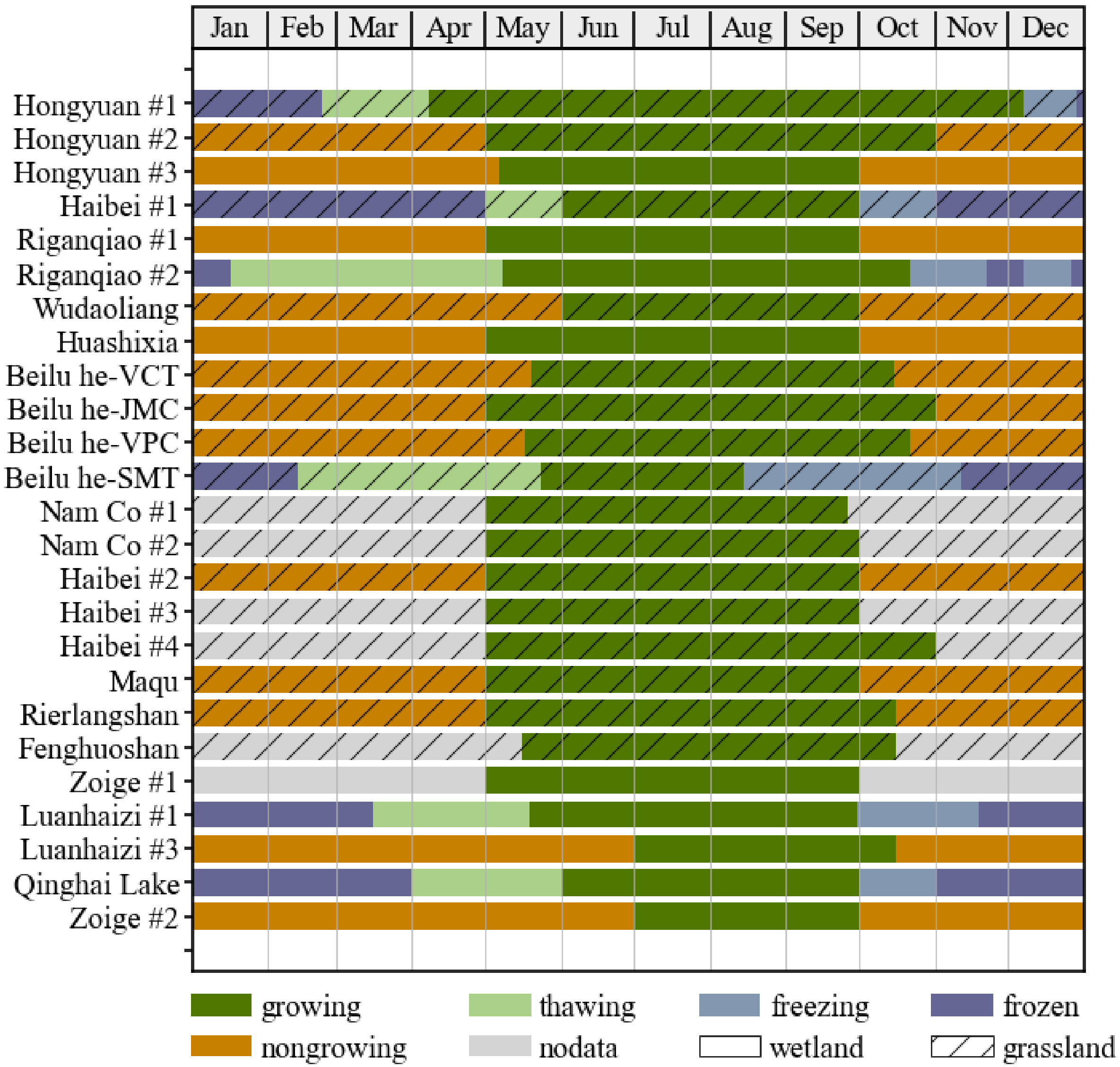


7 sites: raw data

2 sites: replicable text

18 sites: extracted by GetData

Seasonal division

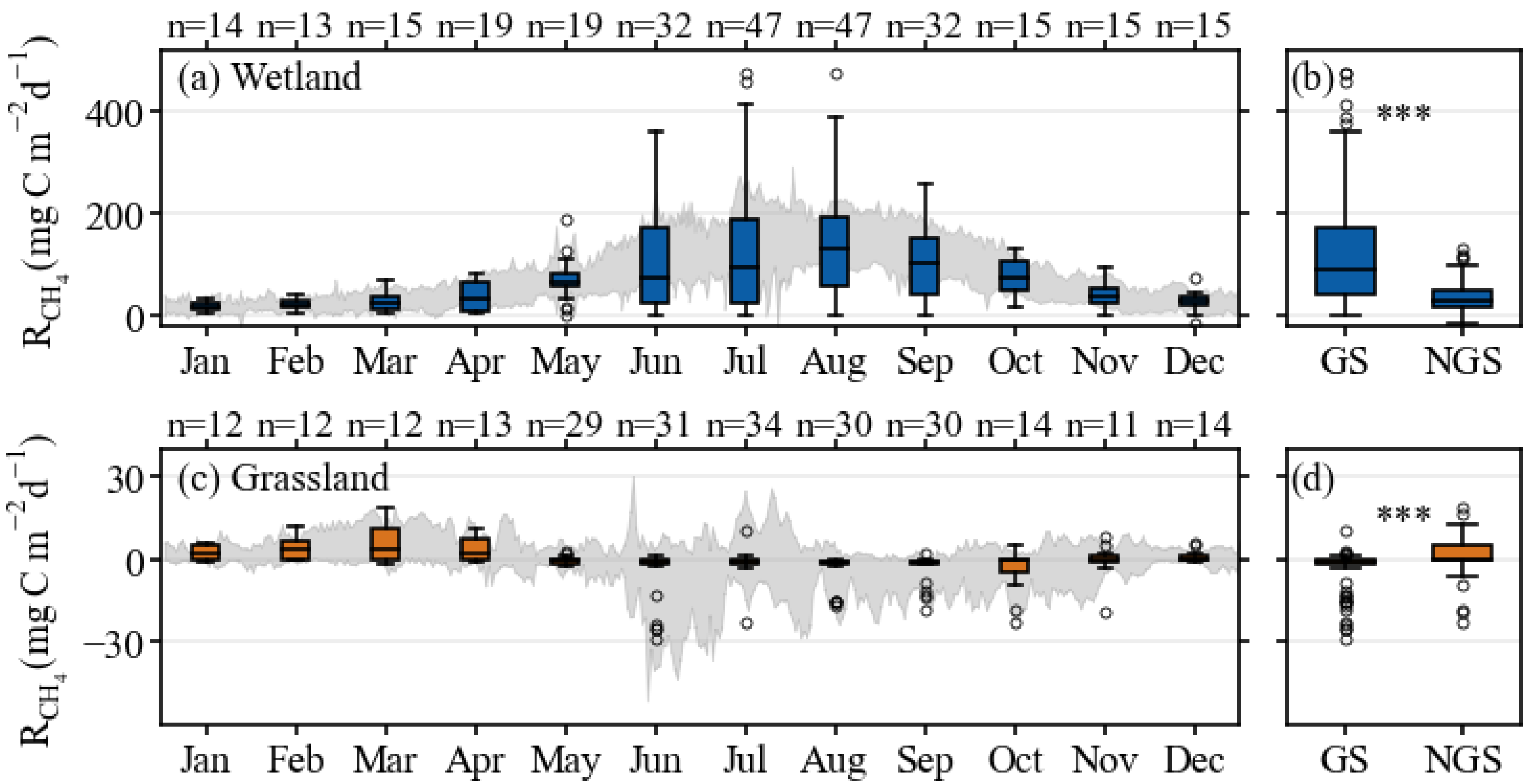


Major seasonal division methods for CH4-related studies in the QTP:

- Soil temperature variation
- Julia day
- Vegetation phenological
- microbial activity

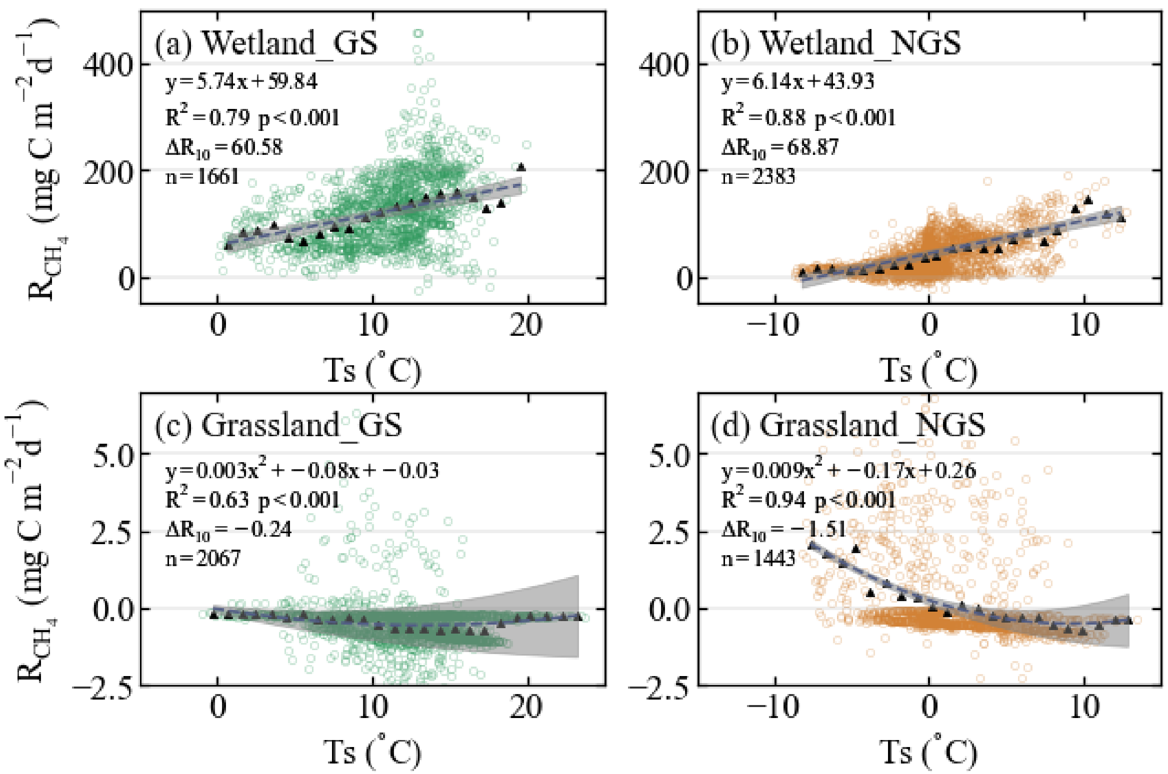
Source and sink of CH_4 on the QTP

- Wetland is the CH_4 source;
- Grassland is the CH_4 sink in the growing season and the CH_4 source in the non-growing season.



Soil temperature-CH_4 fitting

- CH_4 flux showed significant linear or nonlinear relationship with soil temperature in both growing and non-growing season.
- The absolute value of ΔR_{10} in non-growing season was greater than that in growing season.



ΔR_{10}: the changes of CH_4 exchange for every 10°C rise in the soil temperature.

Temperature dependence

Boltzmann-Arrhenius function

$$\ln R_i(T) = (\bar{E} + \epsilon_E^i)\left(\frac{1}{kT_C} - \frac{1}{kT}\right) + \overline{\ln R(T_C)} + \epsilon_R^i$$

- The mixed-effects models could make up for the shortcomings of fitting analysis that is not conducive to multi-site integration analysis and **find the consistent law from the differences of multi-sites**.

- A larger activation energy indicates higher sensitivity to temperature changes.

Published: 19 March 2014

Methane fluxes show consistent temperature dependence across microbial to ecosystem scales

Gabriel Yvon-Durocher, Andrew P. Allen, David Bastviken, Ralf Conrad, Cristian Gudasz, Annick St-Pierre, Nguyen Thanh-Duc & Paul A. del Giorgio

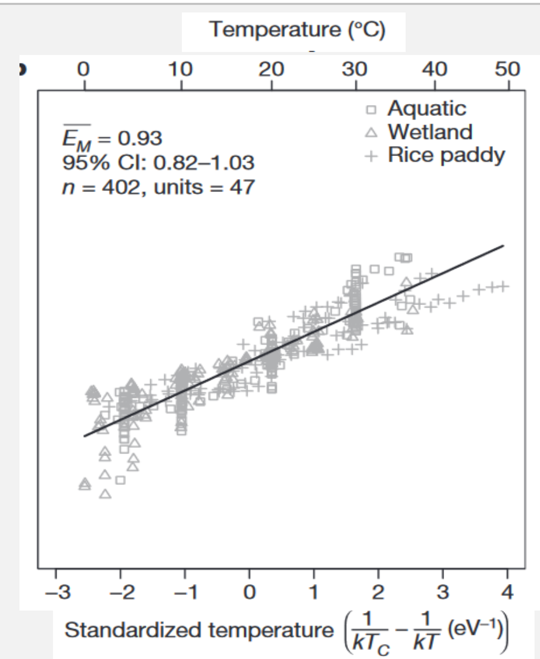
Nature **507**, 488–491 (2014) | Cite this article

Article | Published: 09 August 2021

Differences in the temperature dependence of wetland CO_2 and CH_4 emissions vary with water table depth

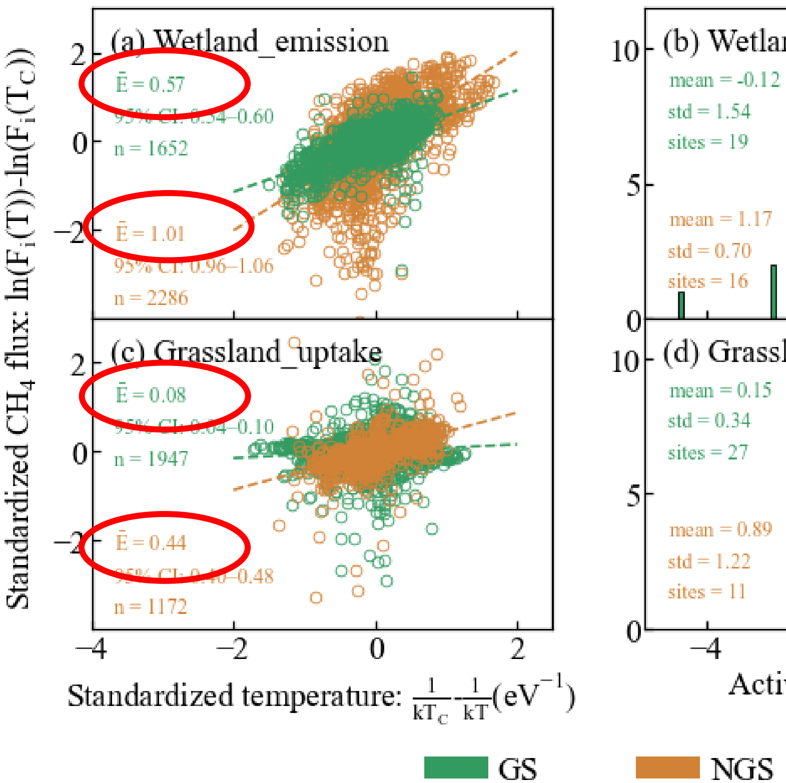
Hongyang Chen, Xiao Xu, Changming Fang, Bo Li & Ming Nie

Nature Climate Change **11**, 766–771 (2021) | Cite this article

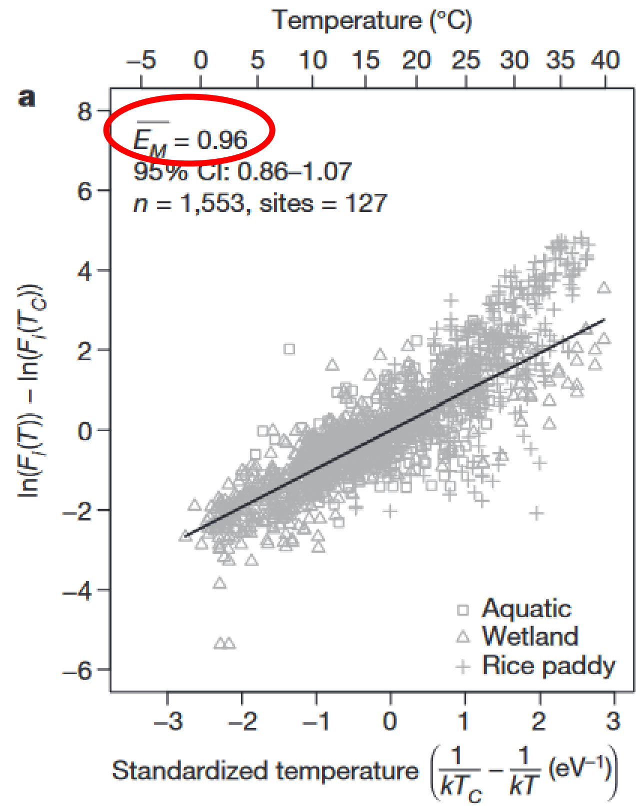


Temperature dependence

- The temperature dependence of **wetland CH_4 emission and grassland CH_4 absorption was stronger in non-growing season than in growing season.**



QTP

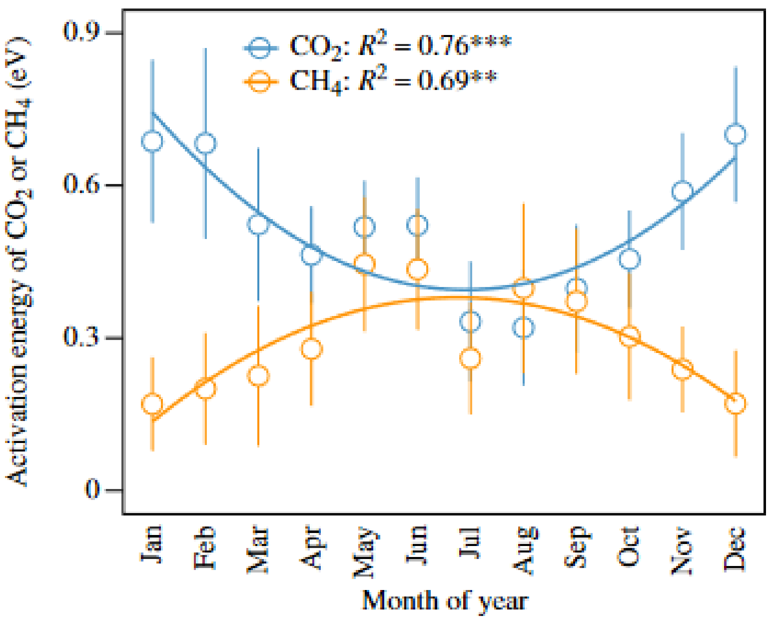


(Yvon-Durocher et al., 2014, *Nature*)

Global

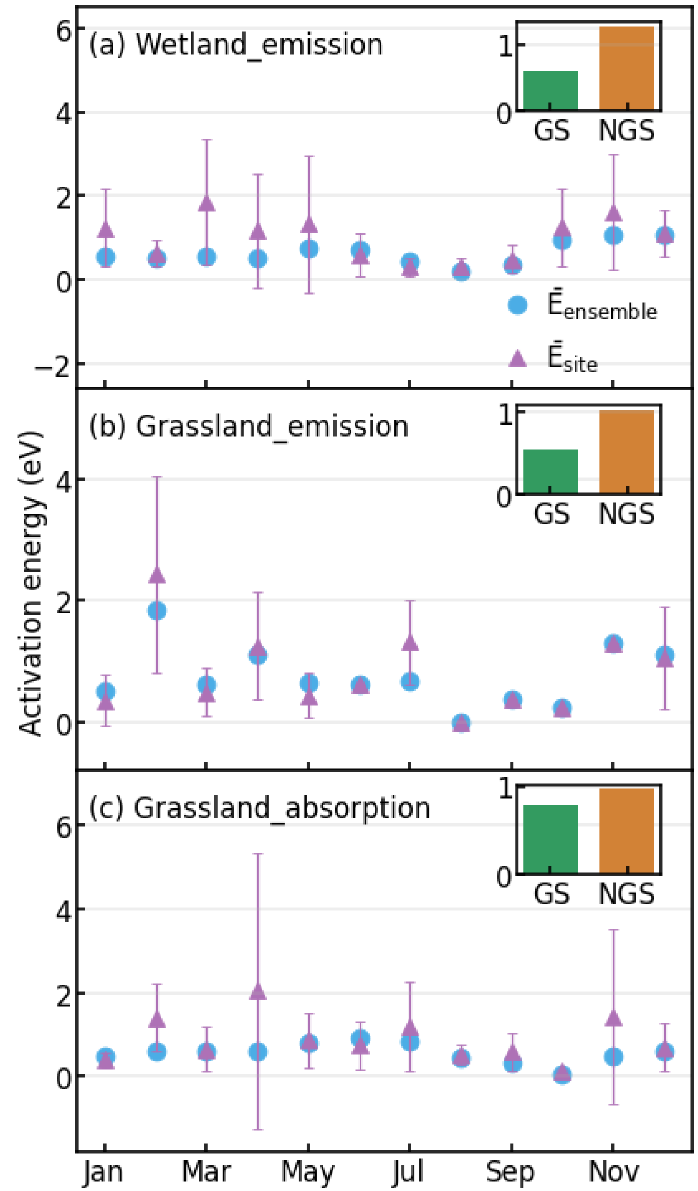
Temperature dependent seasonality differ with global

- The CH_4 temperature dependence of QTP wetland and grassland was stronger than that in the non-growing season.



(Li et al., 2023, GCB)

Global (without QTP)

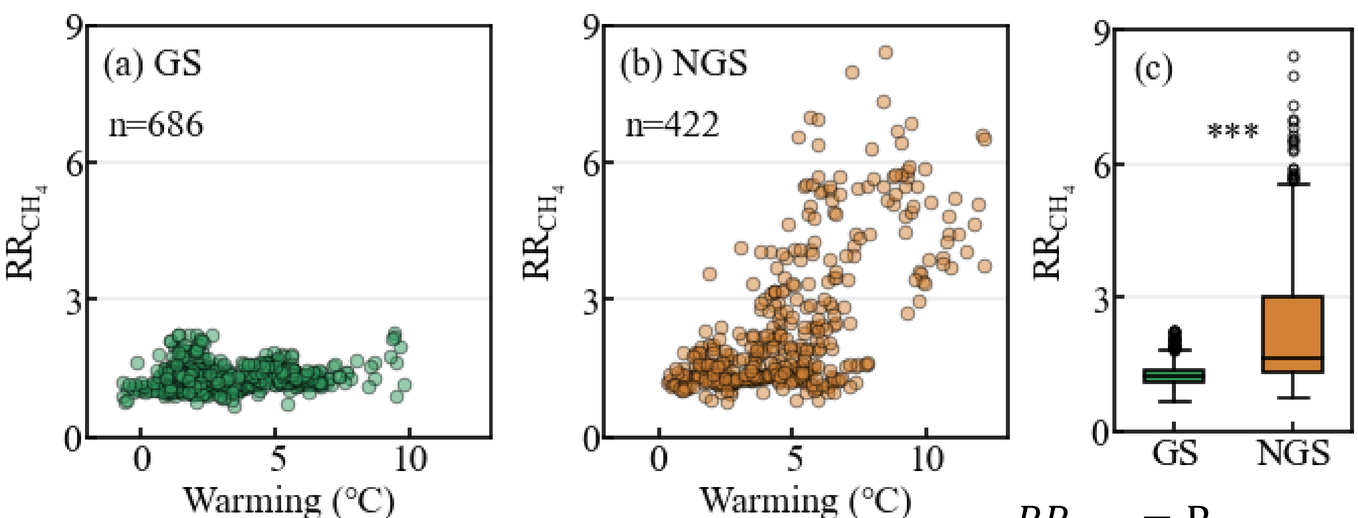


QTP

Control experiment

- **Integrated analysis of three warming experiments on grasslands;**

	growing season	**non-growing season**
average warming magnitude	2.90±1.78℃	4.26±2.33℃
average change rate of CH_4	1.29±0.24 times	1.77±0.93 times



Hongyuan: Western QTP

(Wang et al., 2021, AFM)

(Wang et al., 2022, GCB)

FenghuoShan: Central QTP

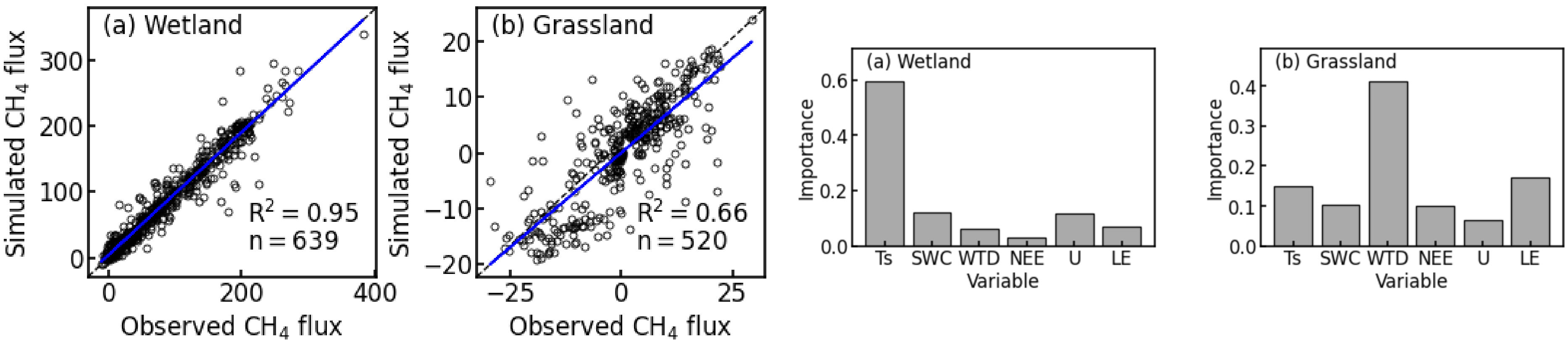
(Chen et al., 2017, STTE)

$$RR_{CH_4} = \mathrm{R}_{CH_4\_\mathrm{warming}}/\mathrm{R}_{CH_4\_\mathrm{contral}}$$

Soil warming and the response of CH_4 in non-growing season were stronger than those in growing season.

Machine learning modeling

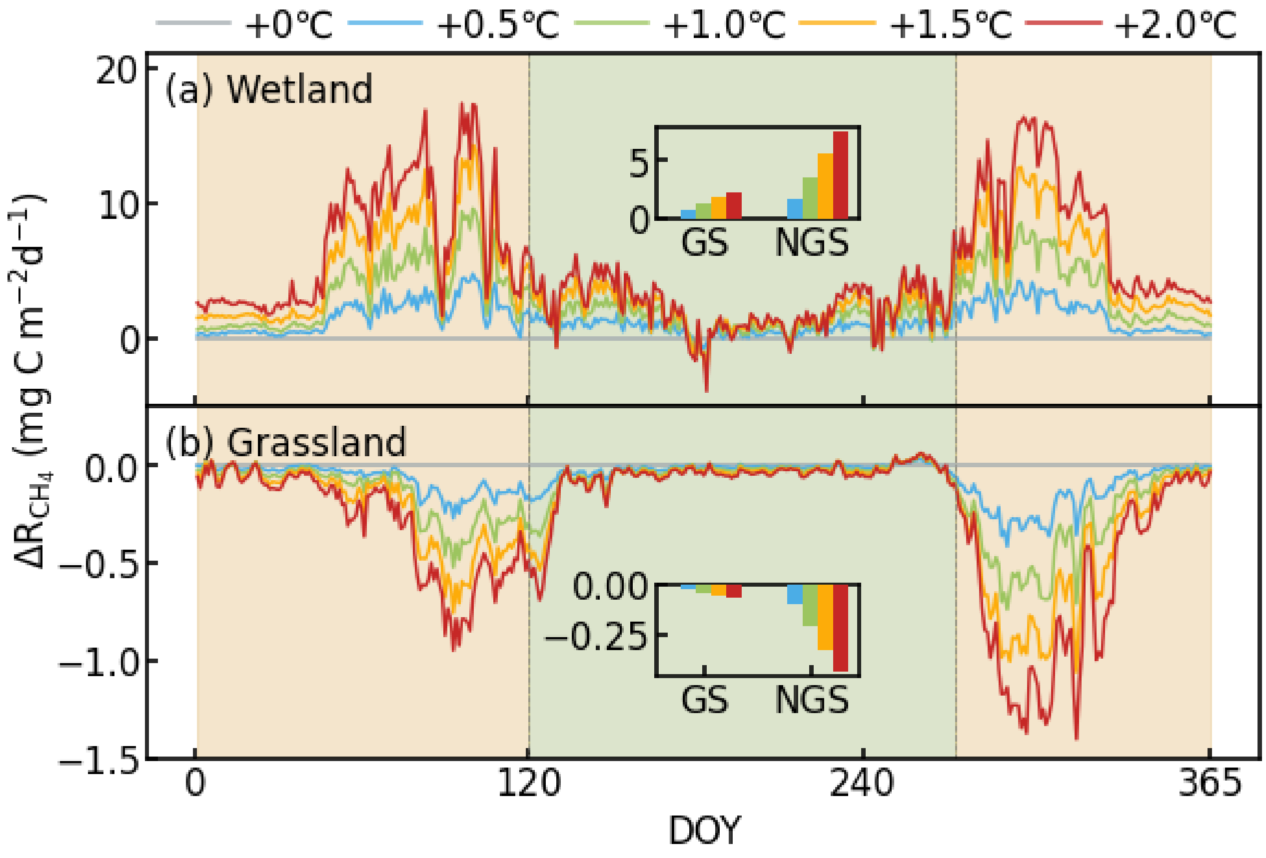
Random forest method was used to train and fit the relationship between environmental impact indicators and methane flux.



Variables	Mechanistic relationship	Description of regional data
NEP	Net ecosystem productivity (carbon substrates and respiration)	Net ecosystem productivity simulated by BEPS model (daily, 1981–2019; 8 km, global)
WTH	Water table height (anaerobic condition or barrier for the CH_4 transport)	Groundwater table depth (monthly, single year; 1 km, global)
SWC	Soil water content	ERA5-Land volumetric soil water layer 1 (hourly, 1950–2023; 0.1°, global)
Ts	Soil temperature (enzyme kinetics)	ERA5-Land soil temperature level 1 (hourly, 1950–2023; 0.1°, global)
U	Friction velocity (CH_4 transport related to turbulence)	CRU-JRA v2.2 wind speed (6-hourly, 1901–2019; 0.5°, global)
LE	Latent heat flux (plant-mediated CH_4 transport related to transpiration)	MODIS MOD16A2 Version 6 Latent Heat Flux (8-day, 2001–2023; 500 m, global)

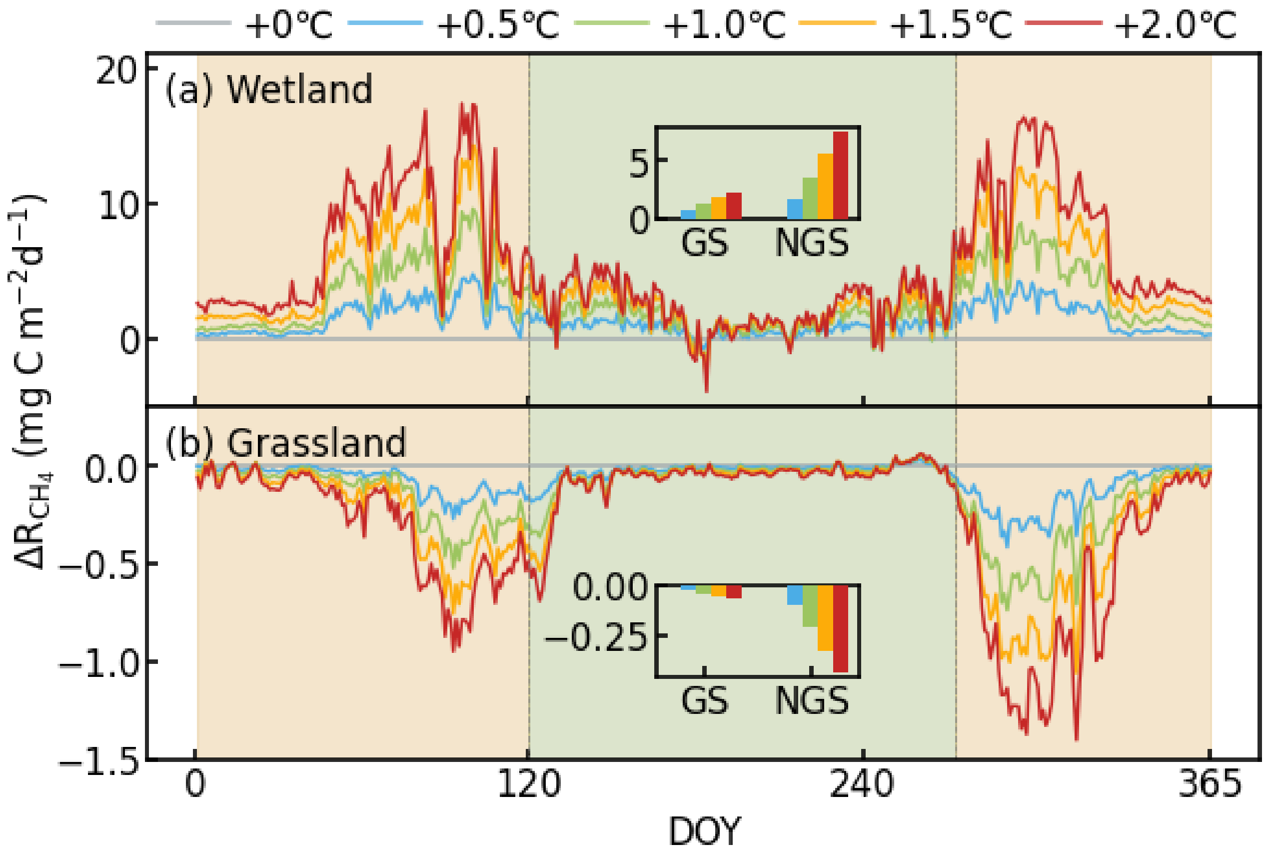
Machine learning modeling

Five simulation schemes were designed with daily soil temperature increasing by +0°C (control), +0.5°C, +1.0 °C, +1.5 °C and +2.0 °C, respectively, to simulate the temporal and spatial changes of methane fluxes in wetland and grassland areas on the QTP.



Machine learning modeling

- Wetland CH4 emission and grassland CH_4 absorption increased with soil warming.
- With the increase of control warming, the difference of CH_4 between growing and non-growing season gradually increased.
- The transition period (melting and freezing), the change was the largest.



Outlook

- With climate warming and permafrost degradation, wetlands and grasslands on the QTP have been experiencing continued expansion and shrinking and this will result in increasing uncertainty of CH_4 emissions and uptakes on the QTP.

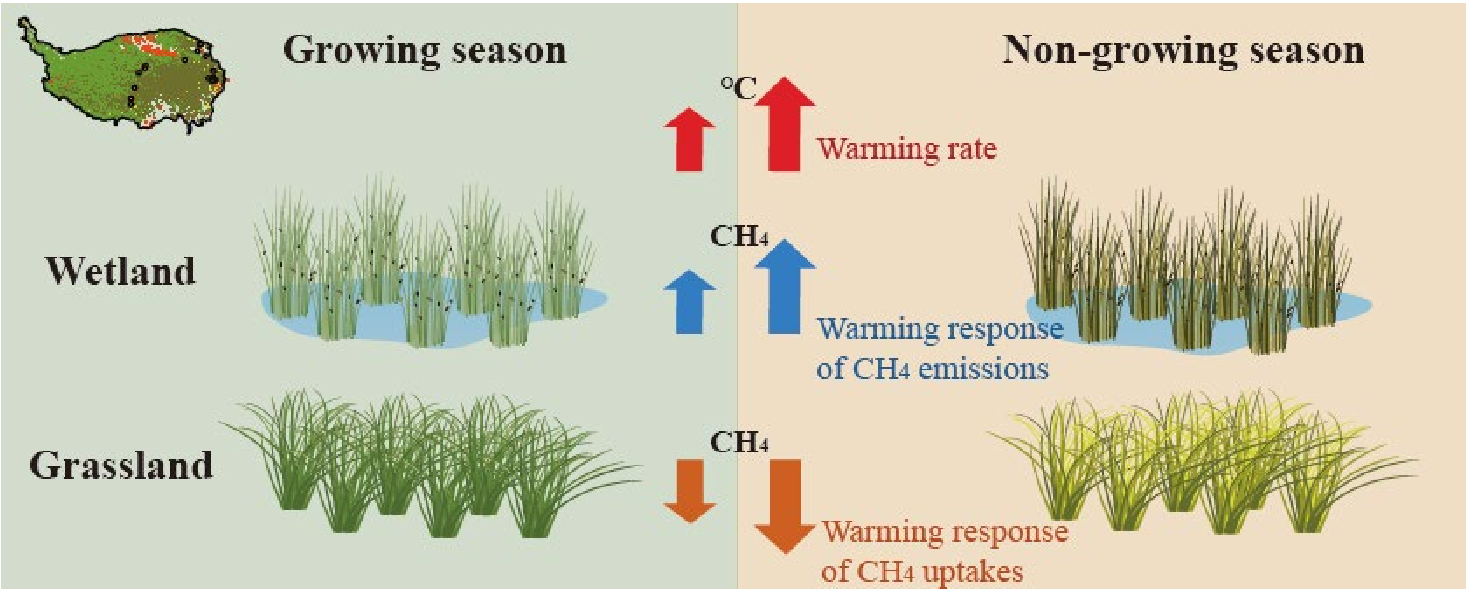
Permafrost degradation -> humidification

Seasonal frozen soil degradation -> desertification

- Therefore, a clear understanding of the seasonality of CH_4 exchange and its response to soil warming will be beneficial to the estimation of the CH_4 budget over the QTP.

Conclusions

- Our study highlights that warming promoted CH_4 emissions in wetlands and uptakes in grasslands on the QTP.
- CH_4 exchange has stronger response to warming in the non-growing than growing season.
- The temperature dependencies of CH_4 exchange of the QTP exhibit different seasonality with the global wetlands, which are stronger during the warmer growing season (Li et al., 2023a).
- Uneven seasonal warming and responses of CH_4 exchange jointly regulate QTP being an ecosystem CH_4 source or sink.



THANK YOU

Data type	Location	Lat. (°N)	Lon. (°E)	Alt. (m)	Ecosystem	Dominant plant species	Source
Raw data	Hongyuan #1	32.80	102.97	3500	Alpine meadow	*Deschampsia caespitosa*	(Wang et al., 2022)
	Hongyuan #2	32.8	102.55	3500	Alpine meadow	*Anemone rivularis*	(Wang et al., 2021)
	Hongyuan #3	32.77	102.50	3510	Alpine wetland	*Carex mulieensis* and *Kobresia tibetica*	(Peng et al., 2021, 2019)
	Haibei #1	37.62	101.32	3250	Alpine meadow	*Kobresia humilis*	(Li et al., 2022)
	Luanhaizi #1	37.58	101.33	3250	Alpine wetland	*Carex pamirensis*	(Song et al., 2015)
	Riganqiao #1	33.11	102.64	3646	Alpine wetland	*Carex mulinesis*	(Zhang et al., 2020)
	Riganqiao #2	33.10	102.65	3460	Fen	*Carex muliensis*	(Chen et al., 2021)
Literature based (table)	Wudaoliang	35.12	93.05	4767	Alpine steppe	*Stipa purpurea*	(Pei et al., 2003)
	Huashixia	35.65	98.80	4400	Alpine wetland	-	(Jin et al., 1999)
Literature based	Beilu' he	34.15	92.06	4765	Alpine steppe	*Carex moorcroftii*	(Yun et al., 2018)
	Nam Co #1	30.77	90.99	4730	Alpine steppe	*Stipa purpurea*	(Wei et al., 2012)
	Nam Co #2	30.00	90.98	4730	Alpine steppe	*Stipa purpurea*	(Wei et al., 2015)
	Naqu	32.17	91.47	4620	Alpine steppe	*Stipa purpurea*	(Wan et al., 2010)
	Haibei #2	37.62	101.33	3250	Alpine meadow	-	(Jiang et al., 2010)
	Haibei #3	37.62	101.32	-	Alpine meadow	*Kobresia humilis*	(Fang et al., 2014)
	Haibei #4	37.62	101.32	-	Alpine meadow	*Kobresia humilis*	(Zhang et al., 2013)
	Maqu	35.97	101.88	3650	Alpine meadow	-	(Liu et al., 2012)
	Nam Co #3	30.00	91.02	4900	Alpine meadow	*Kobresia pygmaea*	(Wei et al., 2015)
	Rierlangshan	34.04	102.72	3326	Alpine meadow	*Deschampsia littoralis*	(Yao et al., 2019)
	Fenghuoshan	34.73	92.89	4763	Swamp meadow	*Kobresia tibetica*	(Chen et al., 2017)
	Luanhaizi #2	37.58	101.33	3250	Alpine marsh	*Carex pamirensis*	(Jin et al., 2015)
	Zoige #1	32.78	102.53	3470	Alpine marsh	*Carex muliejsis* and *Carex meyeriana*	(Wang et al., 2002)
	Huahu Lake	33.10	102.03	3430	Alpine wetland	-	(Chen et al., 2009)
	Luanhaizi #3	37.48	101.20	3250	Alpine wetland	-	(Hirota et al., 2004)
	Qinghai Lake	36.70	100.78	3228	Alpine wetland	*Kobresia tibetica* and *Blysmus sinocompressus*	(Wu et al., 2021)
	Riganqiao #3	33.11	102.64	3646	Alpine wetland	*Carex mulinesis*	(Zhang et al., 2020)
	Zoige #2	33.93	102.87	3430	Fen	*Kobresia tibetica*	(Chen et al., 2013)