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Original Research

Effects of Landuse Change on CH_4 Soil-Atmospheric Exchange in Alpine Meadow on the Tibetan Plateau

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Abstract

Degradation of shrub meadows and reclamation of alpine meadows may heavily affect the soil sink for atmospheric methane (CH_4), but this is poorly understood. Therefore, in situ measurements of atmospheric CH_4 consumption were conducted in four landuse types: natural alpine meadow (NM), *Elymus nutans* pasture (EP), herbaceous meadow in shrub (HS), and a *P. fruticosa* shrub meadow (PS) within two years. CH_4 fluxes were measured using static chambers and gas chromatography. All four types of land use showed atmospheric CH_4 sink throughout the two years, with mean soil CH_4 consumption rates at 24.6±10.9, 33.8±15.0, 39.8±10.3, and 28.1±12.1 μg $CH_4 \cdot m^{-2} \cdot hr^{-1}$ for NM, EP, PS, and HS, respectively. Soil CH_4 consumption increased by 40% by reclamation from NM to EP, while it decreased by 30% by degradation from PS to HS. Soil CH_4 consumption in four types of land use was significantly correlated with temperature at 5 cm depth ($P<0.01$) and the soil water-filled pore space (WFPS) ($P<0.05$). Temperature showed stronger effects on soil CH_4 consumption than WFPS, except in NM. UV radiation was positively correlated with soil CH_4 consumption with increasing temperature and decreasing soil moisture. These findings indicate that a decrease in the grazing pressure in shrub meadows and increase in the area of artificial pasture reclaimed from alpine meadows would enhance the CH_4 sink in alpine meadows on the Tibetan Plateau.

Keywords: alpine meadows, CH_4 consumption, soil water-filled pore space, temperature, landuse change

Introduction

Methane (CH_4) is the second most prevalent greenhouse gas after CO_2 in the atmosphere. Its concentration in air is more than twice the pre-industrial level, and has reached approximately 1,800 ppb in recent years [1], increasing at an annual rate of 1.1% since the pre-industrial era [2]. Aerobic soils have been suggested as a biological process for atmospheric CH_4 and can consume about 20-45 Tg $CH_4 \cdot yr^{-1}$ from the atmosphere [3, 4].

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The global atmospheric CH_4 budget has been significantly affected by anthropogenic activities [5, 6]. Soil CH_4 consumption is sensitive to landuse change, i.e., conversion from forest to farmland [7], natural grasslands to croplands [8], and intensive grassland management [9, 10]. Light grazing had little or a positive impact on soil CH_4 consumption [7, 11], while heavy grazing significantly reduced annual soil CH_4 consumption by 24-31% [7]. Although these disturbances have been confirmed to significantly reduce the soil sink for atmospheric CH_4 [5], it still remains unclear how the land use change from natural meadows to artificial pasture and the degeneration from shrub meadow to herbaceous meadow in shrub meadows affects soil CH_4 consumption.

The Tibetan Plateau is an average of 4,000 m above sea level with an area of about 2.57 million km^2. As such, it is the largest grassland unit on the Eurasian continent. Alpine meadows occupy 35% of the Plateau. However, a large area of alpine meadows are being overgrazed or have been converted from natural meadows to artificial grasslands because of human activities [12]. Meanwhile, some degraded grasslands have been experiencing restoration under human activities. Nonetheless, these land use changes would alter its physico-chemical characteristics, which are of critical importance for soil CH_4 consumption [13]. It remains unclear how these practices affect soil CH_4 consumption in these alpine meadows. UV radiation could strongly enhance CH_4 emissions from vegetation [14], but UV radiation is increasing with the increasing of total solar radiation [15], which could increase temperature of grassland. Soil CH_4 consumption rates have a positive correlation with soil temperature, so UV radiation exerts two negative function on the CH_4 flux from grassland. Here we hypothesized that, first, the land use changes from PS to HS and NM to EP would significantly affect their soil CH_4 consumption capacity. Second, UV radiation would enhance atmospheric methane consumption by soils. To test these hypotheses, we conducted an investigation on the effects of reclamation such as artificial pasture and denegation of shrub meadows on annual CH_4 consumption by alpine meadows on the Tibetan Plateau within two years. Additionally, we analyzed the effects of temperature, moisture, and UV radiation on CH_4 fluxes because these factors have been suggested to greatly affect CH_4 production and oxidation in alpine meadows [14].

Materials and Methods

Ethics Statement

This experiment was established at Haibei Alpine Meadow Research Station (37º32′ N, 101º15′ E, 3,280 m a.s.l.) of the Chinese Academy of Sciences. The study was conducted on alpine meadow, which belongs to Haibei Alpine Meadow Research Station, and involving no cruelty to animals, no damage to habitats and no harm to endangered plants. All the work was carried out under the Wildlife Protection Law of the People's Republic of China.

Study Area

Our study was conducted at Haibei Alpine Meadow Research Station. In the past 20 years, annual mean temperature was -2ºC and annual precipitation averaged 560 mm, of which 85% was concentrated in growing seasons from May to September. Annual air temperature was -1.1 and -0.5ºC in 2004-05, while annual precipitation was 536 and 450 mm, respectively (data from Haibei Alpine Meadow Research Station, CAS).

Experimental Design

Four types of land use (cf. NM, EP, PS, and HS) in a *Kobresia humilis* meadow and a *Potentilla fruticosa* meadow were selected to evaluate the conversion of native grasslands to artificial and degraded grasslands. EP was reclaimed from NM covering an area of 10×10 m, and HS was degraded from PS. There were three replicates for each type. Detailed information about four plant communities was as follows:

i) The native alpine meadow (NM), which is occupied only by a herbaceous layer. Dominant species are *K. humilis* Serg., *Potentilla saundersiana* Royle., *Leontopodium nanum* Hand.-Mazz., *Lancea tibetica* Hook·f·et Thoms., *Festuca ovina* Linn., *Festuca rubra* Linn., *Stipa aliena* Keng., *Helictotrichon tibetica* Henr., *Koeleria cristata* Linna., and *Poa crymophila* Keng.
ii) The artificial pasture (EP), dominant species was *Elymus nutans* Royle. The cultivation of artificial pasture referred to the local herdsmen's method, choosing a flat alpine meadow, ploughing the soil to a depth of 30 cm, smashing the large soil blocks and then sowing the seed of *Elymus nutans* Royle without fertilization. The measurements were conducted one year after sowing, so there was only one year's data for EP.
iii) The shrub meadow (PS) in a native alpine shrub meadow dominated by the shrub *P. fruticosa* and scattered growths in alpine meadows.
iv) The herbaceous meadow (HS) in the *P. fruticosa* meadow, which was occupied by *Festuca rubra*, *Stipa alpine*, *K. humilis*, *E. nutans*, *Polygonum viviparum* L. var. *viviparum*, and *P. saundersiana*.

The soils developed in *Kobresia* and *Potentilla* meadows were Mat-Gryic Cambisol and Mol-Gryic Cambisol, corresponding to Gelic Cambisol [16]. Basic soil property sites are shown in Table 1.

Gas Sampling and Analyses

Gas samples for measurements of CH_4 fluxes were collected weekly during the growing season and every 2 weeks in winter using a closed chamber technique. Plexiglas chambers (length versus width: 50×50 cm) were used to collect CH_4, with 50 cm height for grass communities and 100 cm height for shrub communities. Two small electric fans were used to circulate the chamber air. Gas samples were collected in situ using 100 ml plastic syringes every 10 min over a 30 min period at local time from 09:00-11:00

Table 1. Basic soil properties of the two meadows. Means ±1SE of three replicates are presented.

Meadow type	Soil depth (cm)	PH	Organic C (%)	NO_3-N (%)	NH_4^+-N (%)	Bulk density (g·cm^{-3})
K. humilis meadow	0-10	7.3±0.4	6.2	8.3	11.7	0.75±0.05
	10-20	7.4±0.5	3.8	4.4	5.8	1.11±0.09
	20-30	-	2.7	3.2	4.0	1.13±0.04
	30-40	-	2.3	2.6	3.4	1.15±0.03
P. fruticosa meadow	0-10	6.4±0.2	6.3	7.6	11.3	0.88±0.07
	10-20	6.3±0.3	5.0	5.0	7.8	0.96±0.04
	20-30	-	4.2	3.3	6.0	1.00±0.08
	30-40	-	3.3	2.6	4.8	1.07±0.09

Landuse (NM, EP) was in the *K. humilis* meadow and landuse (PS, and HS) was in the *P. fruticosa* meadow; "-" – indicates no data

Table 2. CH_4 uptake rates (μg CH_4·m^{-2}·hr^{-1}) from different plant communities. Means±standard errors (SE) are presented.

Period	NM	EP	PS	HS
Entire experimental period	24.6±10.9 (n=96)	33.8±15.0 (n=42)	39.8±10.3 (n=94)	28.1±12.1 (n=94)
Growing season	28.4±13.5 (n=46)	45.0±13.0 (n=17)	41.9±12.2 (n=46)	32.2±13.0 (n=46)
Dormancy season	21.0±5.9 (n=50)	26.2±11.6 (n=25)	37.7±7.8 (n=48)	24.2±9.8 (n=48)

to represent daily average flux as described by Cao et al. [17]. The concentration of CH_4 in the gas samples was analyzed on a gas chromatograph (HP Series 4890D, Hewlett Packard, USA) within two days after sampling.

Temperatures at 5 cm depth and at the soil surface, air temperature, and temperature in chamber were measured using a portable digital thermometer (JM 624, JinMing Instrument Co., Ltd., Tianjin, China) at the same time the gas was collected. UV radiation date was obtained from Haibei Alpine Meadow Research Station of the Chinese Academy of Sciences, which was measured by the solar radiation measuring instrument (CM61, Vaisala, Finland). Volumetric soil moisture at 10-cm soil depth was measured with a moisture meter (Time-domain reflectometer, Campbell Scientific, Inc., North Logan, UT, USA). The water-filled pore space (WFPS) was calculated by the dates of soil moisture, bulk density (*BD*) and soil particle density (*PD*) [18]:

$$\mathrm{WFPS} = \frac{volumetric\,soil\,moisture}{(1-(BD/PD))*100}$$

Q_{10} value of CH_4 flux was calculated [19]:

$$F = a \times e^{bt}, \qquad Q_{10} = e^{10b}$$

...where *F* was the soil CH_4 consumption rate, *t* was the soil temperature at 5 cm, and *a* and *b* were constant.

Statistical Analyses

The significant difference for soil CH_4 consumption among treatments and environmental factors were analyzed using ANOVA (LSD method). Multivariate nonlinear regression analysis was performed with SPSS 20.0 (SPSS Inc., Chicago, IL, USA) to evaluate the conjunct influence of soil WFPS and soil temperature at 5 cm on CH_4 fluxes. All differences were tested for significance at $P<0.05$ level with SPSS 20.0 (SPSS Inc., Chicago, IL, USA).

Results

Soil CH_4 Consumption

Mean CH_4 fluxes from the four types of land use were generally negative, i.e. the soils functioned as a net sink for atmospheric CH_4, except for a few plots showing a weak emission of CH_4 in growing season in EP and PS communities (Fig. 1). The soils of four types of land use showed decreasing CH_4 consumption rates in the following order: PS > EP > HS > NM (Table 2). The CH_4 consumption rate of PS soil was significantly higher than those of PS and NM soils ($P<0.01$), while CH_4 consumption rate of EP soil was significantly higher than those of PS and NM soils ($P<0.05$). There was a pronounced seasonal variability of CH_4 fluxes from four types of land use. The soil CH_4 consumption from NM, EP, PS, and HS were significantly higher in growing seasons than in dormant periods ($p<0.01$, Table 2), The total CH_4 flux budget of growing season (June to September) accounted for 38.5%, 41.3%, 35.1%, and 38.2% of the whole year for NM, EP, PS, and HS, respectively.

The conversion from the two native meadows (NM and PS) to artificial grassland (EP) or degraded grasslands (HS) strongly changed the strength of sink for atmospheric CH_4. There was significant difference (P<0.05) between NM and EP, and PS and HS in both growing and dormant seasons. The soil CH_4 consumption rate of the EP increased by 40% compared with the NM, while that of the HS decreased by 30% compared with the PS (Table 2).

Effect of Soil WFPS and Temperature on CH_4 Consumption

Soil WFPS was significantly different among four types of land use. Soil WFPS in the HS was significantly lower than in the PS, while soil WFPS in the EP was significantly lower than in the NM. Significant negative correlation was observed between soil WFPS and soil CH_4 consumption rate of PS (R^2 = 0.03, P<0.05), NM (R^2 = 0.17, P<0.01), EP (R^2 = 0.07, P<0.05), and HS (R^2 = 0.49, P<0.01) (Fig. 2).

The average temperatures of PS, NM, EP, and HS were 5.60, 5.97, 6.29, and 6.89ºC, respectively. Conversions from native meadows to others had little effect on soil temperature and air temperature, i.e. there was no significant difference in temperatures among the four types of land use. Soil CH_4 consumption rates by four types of land use increased significantly (P<0.05) with increasing soil temperature and air temperature. Soil temperature at 5 cm depth explained more the variation of soil CH_4 consumption (PS: R^2 =0.16, P<0.01; NM: R^2 = 0.18, P<0.01; EP: R^2 = 0.28, P<0.01; HS: R^2 = 0.30, P<0.01) (Fig. 3). The Q_{10} values during two years were 1.11, 1.23, 1.39, and 1.37 for NM, PS, EP, and HS, respectively.

Multivariate nonlinear regression analysis showed the combined effect of temperature and WFPS at 5 cm depth on CH_4 fluxes for all four communities (Fig. 4, Table 3). A second order polynomial model was superior compared to other function types (plane, paraboloid, Gaussian, and Lorentzian). This model revealed that the combined effect of WFPS and temperature could explain up to 34% (MM), 29% (EP), 29% (PS), and 42% (HS) of the variations of CH_4 fluxes (Table 3). Of these environmental factors, temperature showed a stronger effect on CH_4 consumption for EP, PS, and HS, while in the NM WFPS demonstrated stronger effects (Fig. 4).

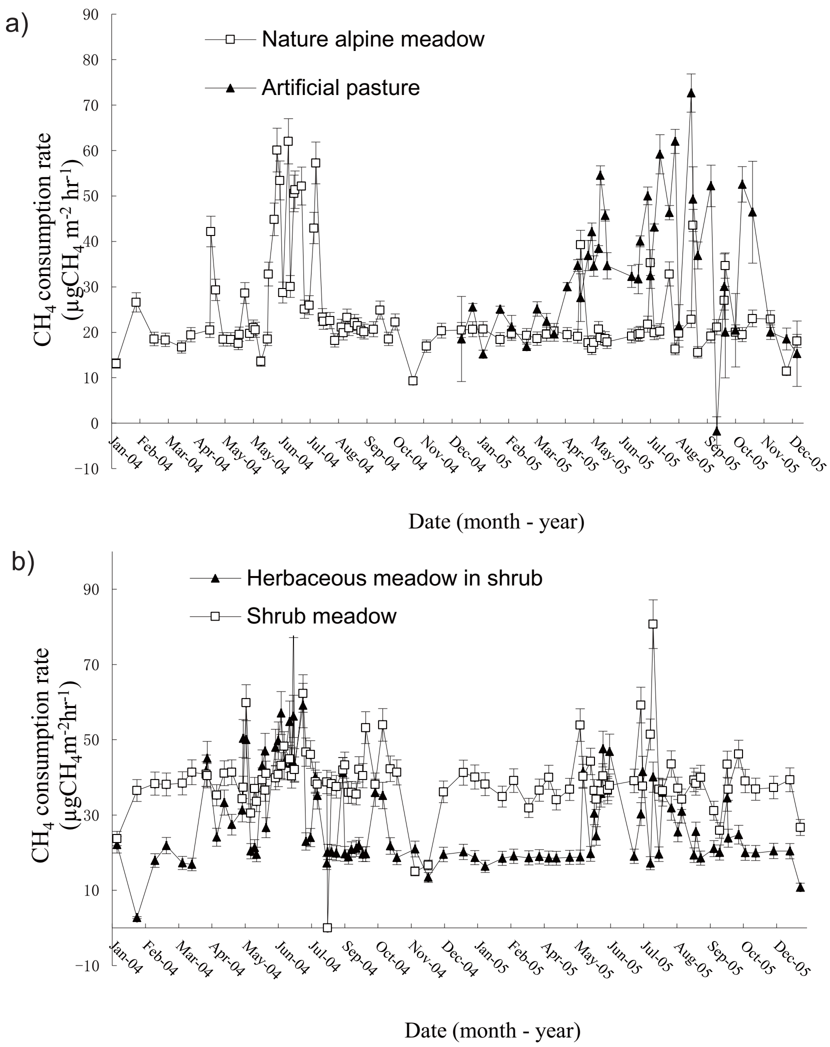

Fig. 1. CH_4 fluxes from the *K. humilis* meadow (a) and *P. fruticosa* meadow (b). Means ±1SE of three replicates are presented.

Table 3. Polynomial equations describing the dependency of CH_4 fluxes on WFPS and temperature (T)[#].

Gas flux = A + B × T + C × WFPS + D × T² + E × WFPS²						
Land use type	R^2	A	B	C	D	E
NM	0.34**	106.750	-0.073	-2.711	0.021	0.021
EP	0.29*	78.175	1.496	-1.917	-0.035	0.015
PS	0.29*	17.369	-0.914	1.003	0.070	-0.010
HS	0.42**	42.567	-0.284	0.038	0.027	-0.005

*Significant at level P<0.05, **Significant at level P<0.001.
[#]Given are the factors and coefficients for maximal R^2.

The Effect of UV Radiation on CH_4 Flux

Strong solar radiation is a very important environmental factor for plants growing on the Tibetan Plateau. The daily average total solar radiation was 1.73 and 2.23 MJ·m^{-2} for 2004 and 2005, and UV radiation was 0.14 and 0.19 MJ·m^{-2}. Soil CH_4 consumption in all four plant communities related poorly to total solar radiation, but it showed a significantly positive correlation with UV radiation (Fig. 5). It was also found that UV radiation had a positive correlation with soil temperature (P < 0.01) and soil WFPS (P <0.05) during the observing period.

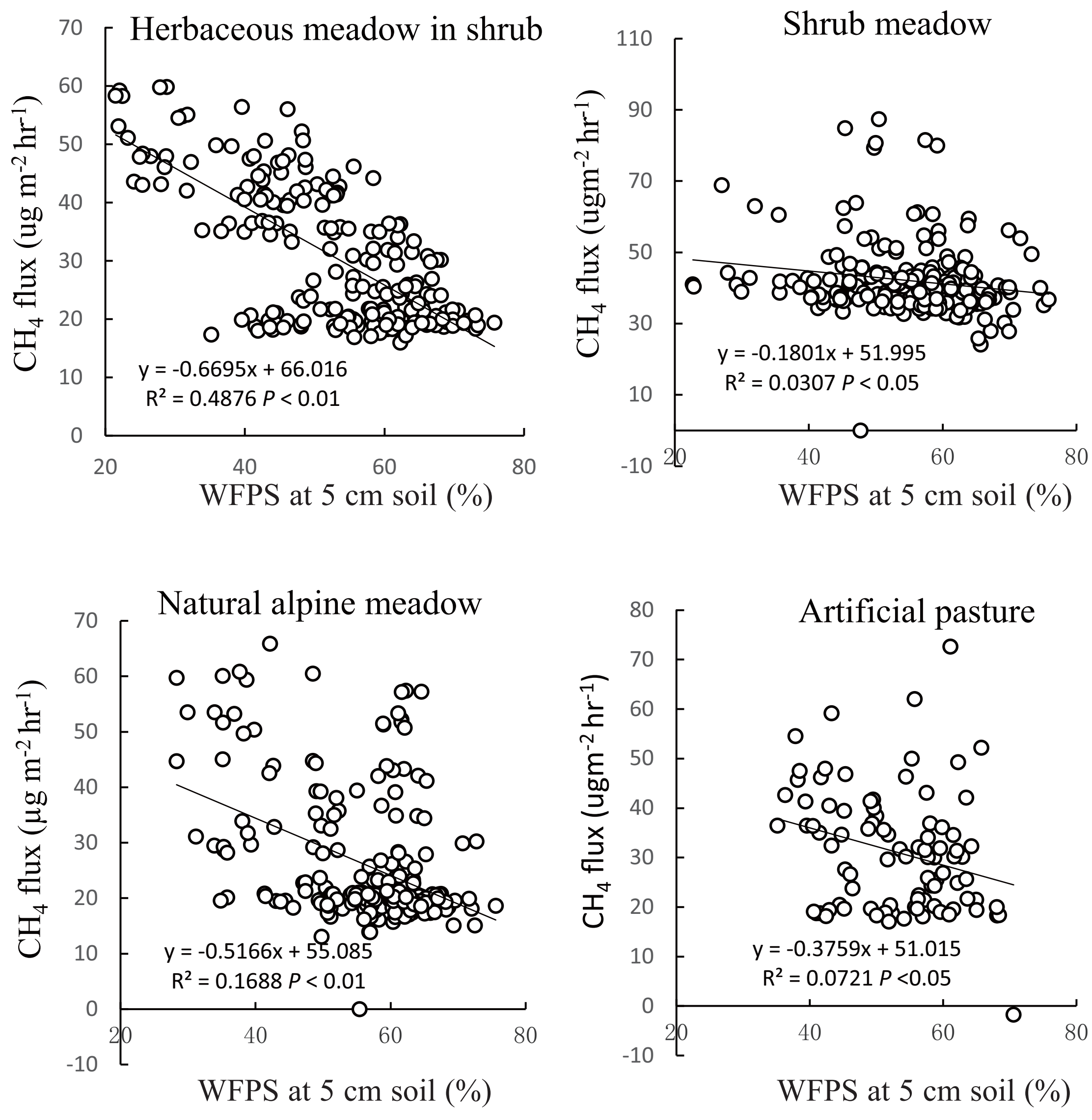

Fig. 2. Relationships between CH_4 uptake rate and soil WFPS at 5 cm depth in four types of land use.

Discussion

During two years' observation our results clearly showed that the four investigated land uses explicitly functioned as a sink of atmospheric CH_4. The mean annual CH_4 consumption for NM, HS, and PS were estimated at 28.1±3.9, 32.1±4.1, and 45.4 kg±6.4 $CH_4{\cdot}ha^{-1}{\cdot}yr^{-1}$ among 2004 and 2005, and EP had a consumption rate at 38.6 kg $CH_4{\cdot}ha^{-1}{\cdot}yr^{-1}$ in 2005. The CH_4 consumption for all types of land use had the same trend: increasing from the beginning of the growing season, reaching maximum consumption rate in July or August, and then gradually declining. These CH_4 consumption values were within the upper range of CH_4 flux rates observed by previous studies on the Tibetan Plateau [9, 20-22]. The soil has a much higher content of organic carbon on the plateau than other grassland soils in China [23], which leads to a higher abundance of methanotrophs in alpine meadow soils [24, 25] and higher soil CH_4 consumption in alpine meadows.

Additionally, numerous studies have shown that land use change can decrease the capacity to take up atmospheric CH_4 [26, 27]. In this study we observed contrary results for conversion from native alpine meadows to artificial grasslands, which increased the soil CH_4 consumption rate by 40%. A possible explanation for this is that artificial grasslands changed soil structure due to tillage and thus enhanced gas diffusion. Although the soil CH_4 consumption ability was greatly enhanced in the EP compared to the NM, the EP is an unstable land use type and would degenerate in later years [28]. In another comparison of land use change, the conversion from the PS to HS decreased the soil CH_4 consumption rate by 30%, this atmospheric CH_4 uptake decrease was also a potential

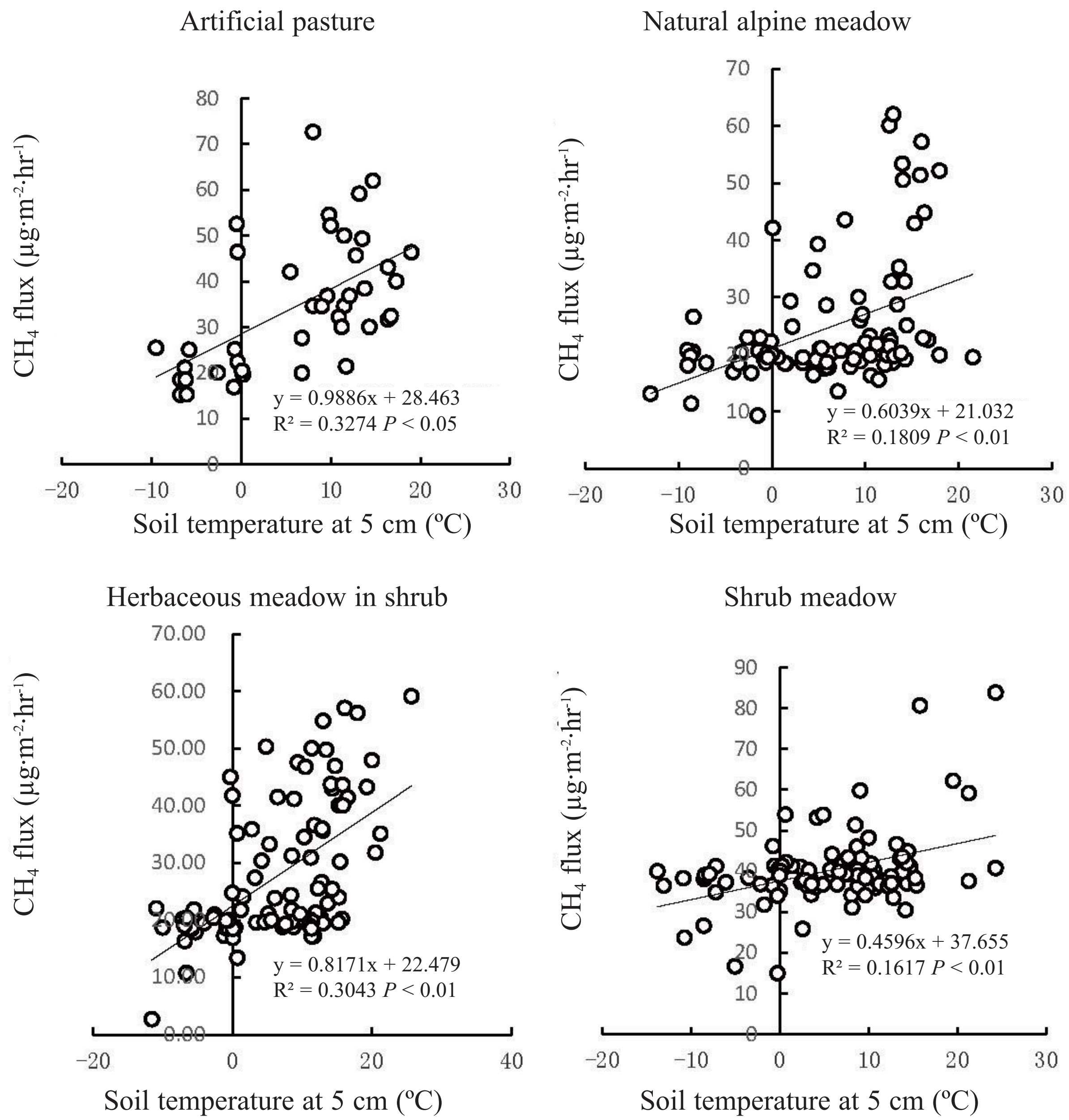

Fig. 3. Relationships between CH_4 uptake rate and soil temperature at 5 cm depth.

CH_4 emission. This potential CH_4 emission may be due to the dominant plant species change, i.e. *P. fruticosa* has the capacity to take up atmospheric CH_4 [17], *P. fruticosa* is a shrub plant, which has the more developed vascular bundle than it in herbs [29], and such structure characteristics make the air more easily into soil so that more CH_4 was oxidated by methanotrophs in soil. However, the heavy grazing resulted in, i.e., *P. fruticosa* population, plant height, density, coverage, and above-ground biomass all decreasing, and 20 years of grazing led to a 8.77% *P. fruticosa* population loss [30]. Herbaceous species became the dominant population, then reduced meadow CH_4 consumption. The result of this study elucidates that the land use change of the native meadow in the Tibetan Plateau can reduce soil CH_4 consumption and also can enhance the capacity of soil CH_4 consumption by soil structure and dominant species change.

Effects of Soil WFPS and Temperature on CH_4 Consumption

Gas diffusion in the soil is controlled by WFPS, showing a negative linear correlation between soil CH_4 consumption rate and soil WFPS [21, 31], which was also observed in our study, however when compared indigenous meadows (NM, PS) with replacement meadows (EP, HS), an inconsistent result was found. Soil aeration is very important for the diffusion of atmospheric CH_4 to the sites of active CH_4 consumption [32]. The WFPS of PS were higher than NM and HS, respectively, but soil CH_4 consumption capacity for shrub meadow (PS) was significantly higher than herbaceous meadows (NM, HS), indicating that soil CH_4 consumption rates were not dependent only on the trend of WFPS. The PS and HS were both in the *P. fruticosa* meadow and have the same soil type and almost the

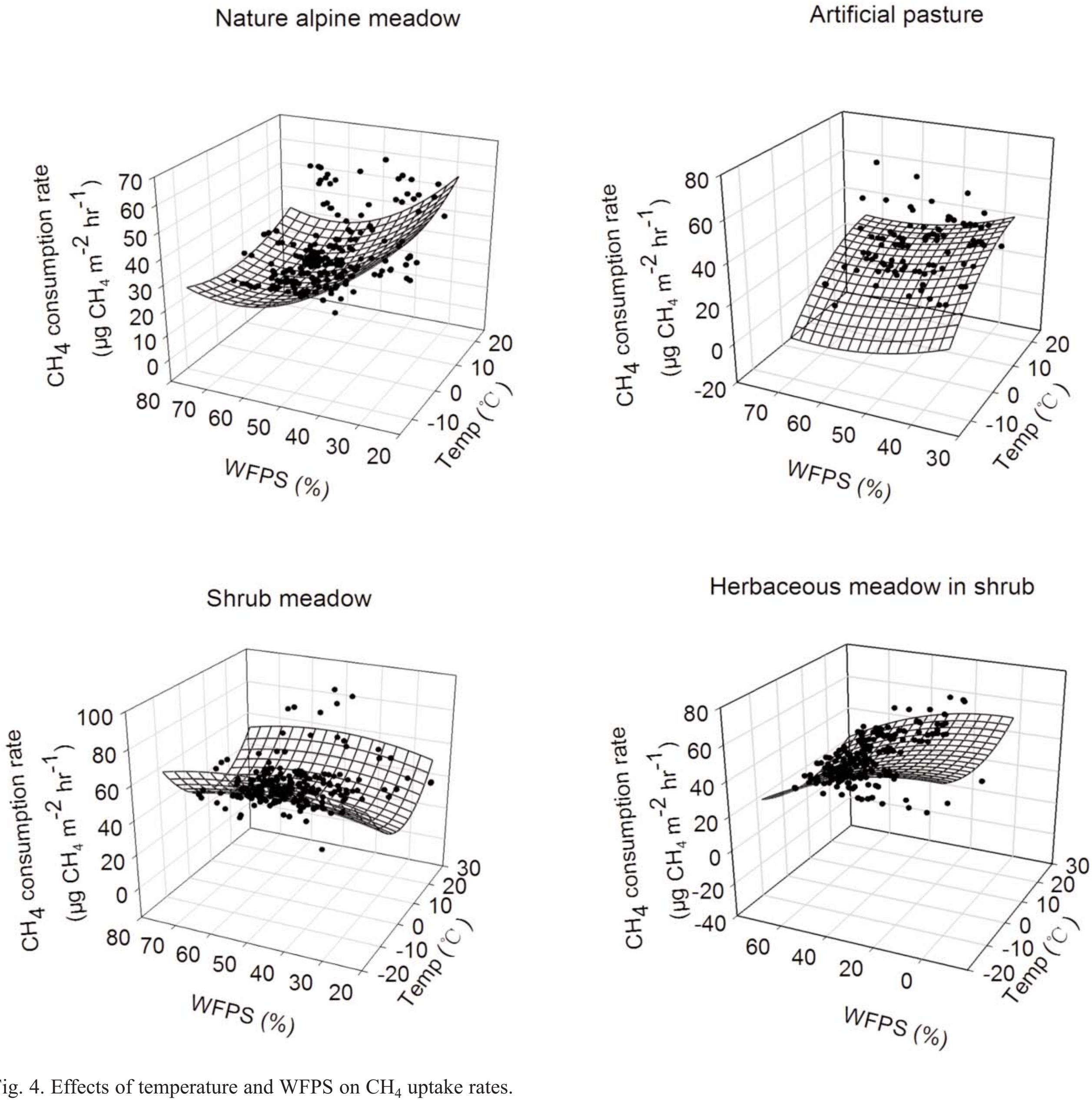

Fig. 4. Effects of temperature and WFPS on CH_4 uptake rates.

same temperature, so there must be other factors in charge of the higher consumption rate of CH_4 in PS. Shrubs have a well-developed vascular bundle than herbaceous plants, which may promote CH_4 of atmosphere passing into soil through the vascular bundle, and compared with herbaceous plants the roots of shrubs could make the soil looser and larger soil porosity, so favoured the aeration and increased the oxidation of atmospheric CH_4. This founding indicates that not only site-specific soil properties and soil aeration, but also plant species were charging the CH_4 soil-atmospheric exchange in alpine meadows.

Multivariate nonlinear regression analysis showed that CH_4 fluxes were mainly influenced by temperature except for the NM. This could be due to its low moisture causing drought stress and low WFPS, which inhibits gas diffusion [32-34]. The explanatory power of multivariate nonlinear regression analysis to CH_4 consumption rate only ranged 29-42%, indicating that there exists some unknown important factors affecting CH_4 fluxes. Therefore, we cannot expect to use a simple relationship between environmental factors and CH_4 fluxes to describe and predict CH_4 fluxes in alpine meadows [32]. Further investigations are needed to clarify unknown important factors controlling CH_4 fluxes in alpine meadows.

Methanogens and methanotrophs were reported to have different temperature sensitivities and optimum temperature regions [20, 35, 36]. Temperature affects CH_4 emission from vegetation [36], but the plant-soil system demonstrated increased CH_4 oxidation with increasing temperature at 5 cm depth. This indicates that methanotrophs could be more sensitive than methanogens and vegetation in alpine meadows. The Q_{10} values during the two year was 1.11, 1.23, 1.39, and 1.37 for NM, PS, EP, and HS, respectively, suggesting that the soil CH_4 consumption of *P. fruticosa*

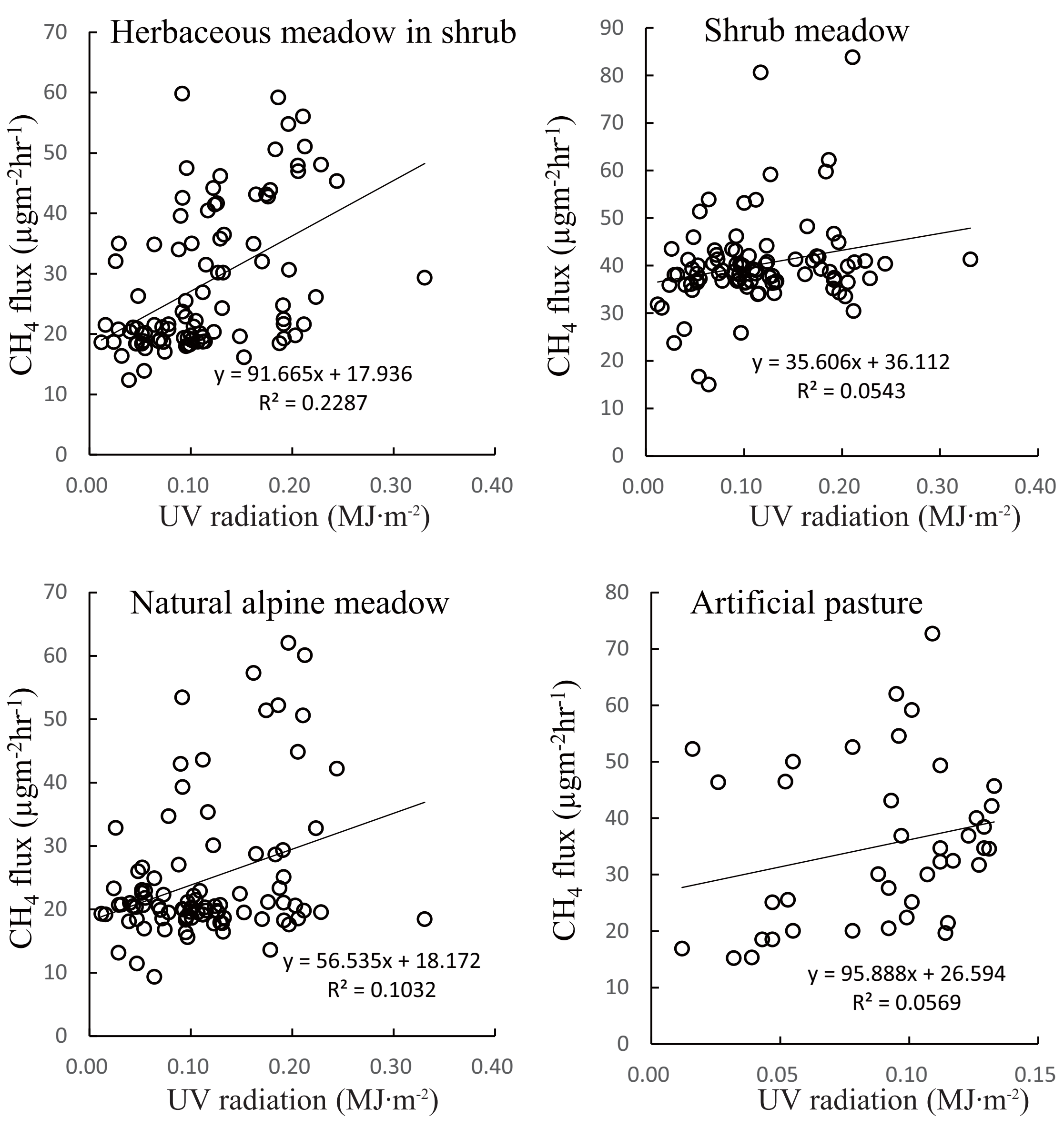

Fig. 5. Relationships between CH_4 uptake rate and UV radiation.

meadow (PS and HS) was more sensitive to temperature than NM and EP, and may have the potential to take up more atmosphere CH_4 under warming conditions.

The Effect of UV Radiation on CH_4 Flux

Our results showed that there are some important factors affecting CH_4 fluxes except temperature and moisture. Here we analyzed the effects of UV radiation on CH_4 fluxes, in this study the CH_4 consumption by soils in all four plant communities showed a significantly positive correlation with UV radiation (Fig. 5), there had been no report about this phenomenon, and the mechanism of methane consumption was methane absorbed by methane oxidative bacteria in the soil pore, UV radiation had a positive correlation with soil temperature ($P<0.01$), and accelerated the bacterial metabolism ability, because the temperature was the main limiting factor of bacterial metabolism on the Tibetan Plateau [24], WFPS also increased with UV radiation ($P<0.01$), made the soil more porous, then increased the methane consumption by meadow soil. Therefore, UV radiation can indirectly enhance CH_4 oxidation through altering soil temperature and moisture in the soil.

Conclusions

The Tibetan Plateau plays an important ecological function in regulating the local climate, and is vulnerable to human activities and global climate change. But until now there has been little data about methane fluxes in alpine meadows. This study demonstrates that land use changes in alpine meadows have greatly affected soil CH_4 consumption. The degeneration of the PS to the HS decreased soil CH_4 consumption by 30%, while the reclamation of the NM to the EP increased soil CH_4 consumption by 40%. Consumption of atmospheric CH_4 by plant communities was more sensitive to temperature than to soil WFPS. UV radiation enhanced consumption of atmospheric CH_4 through exerting effects on soil temperature and WFPS. These findings indicate that the effects of future climate and land use change could increase methane consumption in alpine meadow soils on the Tibetan Plateau.

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