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Increases in the Methane Uptake of Upland Forest Soil in China Could Significantly Contribute to Climate Change Mitigation

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Abstract: Upland forest soil is an important CH_4 sink that plays a key role in climate change mitigation. China features large areas of various types of forest, but spatiotemporal variation in CH_4 flux has not yet been clarified. Here, we analyzed variation in CH_4 flux and the effects of environmental variables on the CH_4 flux of forest in China using in situ observational data. Upland forest soil absorbed CH_4 at a rate of 0.24 ± 0.02 g m^{-2} yr^{-1}. The CH_4 uptake rate (0.46 ± 0.10 g m^{-2} yr^{-1}) of warm temperate deciduous broad-leaved forest was the highest. Soil alkali-hydrolyzable nitrogen was the only factor significantly correlated with CH_4 uptake variation among vegetation zones. A break point in CH_4 uptake over the study period (from 1997 to 2020) was detected in 2015. CH_4 uptake slightly decreased until 2015 and increased after 2015. The mean CH_4 uptake of the period after 2015 (0.44 ± 0.07 g m^{-2} yr^{-1}) was significantly higher than that before 2015 (0.20 ± 0.02 g m^{-2} yr^{-1}). Atmospheric nitrogen deposition was negatively related to interannual CH_4 uptake. Our findings suggest that the CH_4 uptake of upland forest soil will continue to increase over the next few decades as China accelerates efforts to achieve its carbon neutrality goal, and this would result in continuous decreases in nitrogen deposition through various pathways.

Keywords: CH_4 uptake; forest types; long-term variation; environmental variable; nitrogen deposition

1. Introduction

Methane (CH_4) is the second most important anthropogenic greenhouse gas in the atmosphere following carbon dioxide, and it has contributed 0.5 °C of warming from 2010 to 2019. By comparison, the temperature rise caused by CO_2 emissions over the same period was 0.73 °C [1]. Some of the highest levels of anthropogenic CH_4 emissions are in eastern Asia; consequently, CH_4 emission-induced temperature increases in eastern Asia are several times higher than those reported in other regions [2].

Forest soil is the largest CH_4 sink among terrestrial ecosystems; on a global scale, forest soil absorbed 9.16 ± 3.84 Tg CH_4 per year from 1981 to 2010 [3,4], which is approximately 1/3 of the CH_4 emissions associated with rice cultivation [5]. Soil CH_4 uptake is an economically efficient, long-lasting, and multifunctional approach for climate change mitigation [6]. Therefore, accurate estimates of CH_4 uptake by forest soil are important for regulating the global CH_4 budget and providing key information for policymakers responsible for developing climate mitigation policies. However, estimates of CH_4 uptake reported in various studies are inconsistent, and the cause of these inconsistencies remains unclear [3,7,8]. A lack of knowledge of fundamental concepts likely explains the large discrepancies among models in their representation of CH_4 processes as well as their environmental controls [9].

There is a high degree of variation in temperature, precipitation, topography, and forest type in China [10]. However, to the best of our knowledge, only two regional studies

have examined forest CH_4 uptake in China to date [11,12]. In the first study, CH_4 uptake by forest in China was estimated using observational data from 26 sites [11]. In the second study, CH_4 uptake rates of different ecoregions and the effects of litter removal and nitrogen (N) addition were analyzed [12]. Long-term variation in CH_4 uptake by forests in China has not yet been analyzed.

Here, we characterized (1) variation in the CH_4 uptake of forest soil in areas differing in vegetation (forest types) in China, (2) long-term trends in CH_4 uptake, and (3) relationships between environmental variables and CH_4 uptake using in situ observational data. Our findings shed new light on the relative importance of forest CH_4 uptake in climate change mitigation.

2. Materials and Methods

2.1. CH₄ Flux Data

We compiled studies from the China National Knowledge Infrastructure (CNKI) and Web of Science database using the following criteria: (1) measurements of forest soil CH_4 flux were conducted in situ; (2) the chamber method, including self-made chambers and commercial products, was used to take CH_4 flux measurements; (3) no manipulations were conducted during data collection (e.g., fertilization, water reduction, and litter removal); and (4) the sampling period was at least 4 months. Data in figures were extracted using GetData Graph Digitizer software (Version 2.25, GetData Software, Kogarah, Australia). We acquired chamber-observed in situ CH_4 flux data for 4 sites from the ChinaFLUX platform (http://159.226.111.42/pingtai/LoginRe/dataservice2.jsp, accessed on 28 October 2016). Annual CH_4 flux data from previous studies and ChinaFLUX were derived by averaging all observations in a year. We extracted the annual CH_4 flux of forest in China from five published reviews and meta-analyses [3,12–15]. Duplicate records among different sources were omitted based on the location and reported sampling time.

A total of 277 annual CH_4 estimates were obtained (Figure 1a), including 138 records from observational studies, 27 records from the ChinaFLUX platform, and 112 records from published review papers. These records were taken from a wide range of forest types and environments (Figure 1). According to China's vegetation zones [16], the dataset covers all forest zones and a grassland zone in which forest growth is sparse (Figure 1a).

2.2. Environmental Data

To analyze the effects of environmental variables on spatiotemporal variation in CH_4 flux, precipitation, temperature, N deposition, and soil parameter data were collected. Annual mean temperature (MAT, °C), annual precipitation (MAP, mm), and soil water content (SWC, mm) were obtained from global climate archives (0.5-degree, monthly) provided by the NOAA/OAR/ESRL PSL, Boulder, CO, USA [17–19]. Soil parameters were obtained from a China soil dataset (30 arc-seconds) [20], including soil organic matter (SOM, g/100 g), total N (TN, g/100 g), alkali-hydrolysable N (AN, mg/kg), total phosphorus (TP, g/100 g), available phosphorus (AP, mg/kg), total potassium (TK, g/100 g), available potassium (AK, mg/kg), pH, bulk density (BD, g/cm^3), porosity (POR, cm^3/100 cm^3), and rock fragments (GRAV, g/100 g). Soil conditions were assumed to be constant across the study period (1997–2020). Atmospheric N deposition was obtained from a China inorganic N wet deposition dataset (1 km) [21], including ammonium N (abbreviated as NH_4, kg N ha^{-1} yr^{-1}), nitrate N (abbreviated as NO_3, kg N ha^{-1} yr^{-1}), and dissolved inorganic N (DIN, sum of ammonium N and nitrate N, kg N ha^{-1} yr^{-1}). The N deposition data were from 1996 to 2015 over 5-year intervals. Therefore, N deposition data and flux data were organized by period and N deposition data after 2015 were treated as unavailable.
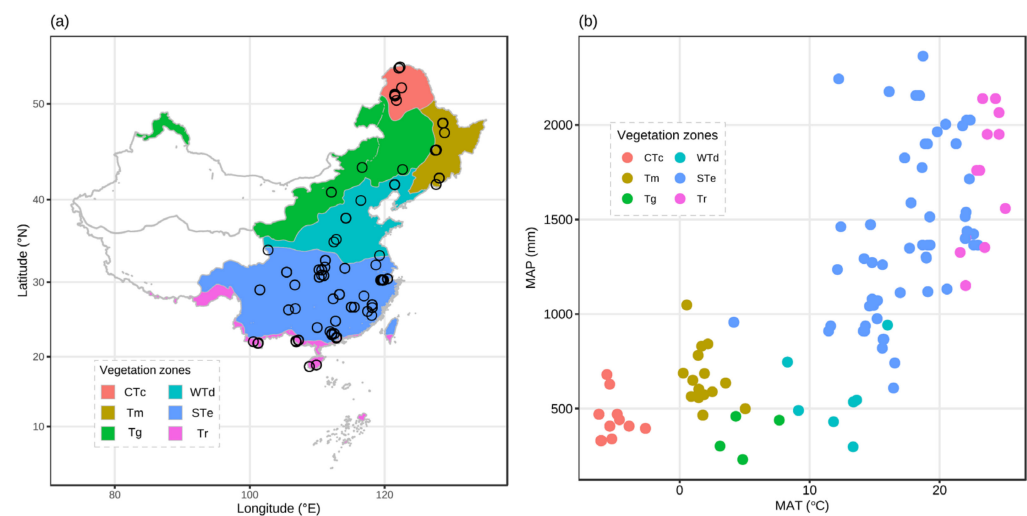
Figure 1. Distribution of sampling points. (**a**) Geo-location of the sampling points; (**b**) Distribution of sampling points along mean annual temperature (MAT) and mean annual precipitation (MAP) gradients. CTc denotes cold temperate coniferous forest area, Tm denotes temperate coniferous and deciduous broad-leaved mixed forest area, Tg denotes temperate grassland area, WTd denotes warm temperate deciduous broad-leaved forest area, STd denotes subtropical evergreen broad-leaved forest area, and Tr denotes tropical monsoon rainforest and monsoon rainforest area. The areas without colors (**a**) are areas covered by grassland, meadow, and desert.

2.3. Statistical Analysis

Wilcoxon–Mann–Whitney tests were used to analyze differences among different zones and periods using the "coin" package [22]. Long-term flux variation was analyzed using locally weighted regression (loess). Piecewise regression was carried out to determine the break point using the "segmented" package [23,24]. The random forest algorithm was used to compare the relative importance of different environmental factors affecting spatiotemporal variation in CH_4 uptake [25]. This analysis was carried out using the packages "randomForest" and "rfUtilities" [26,27]. Correlations between environmental factors and fluxes were conducted using Spearman correlation analysis and partial correlation analysis with the "ppcor" package [28]. A probability value (*p* value) less than 0.05 was considered statistically significant.

All statistical analyses and plotting were conducted in R [29] with the aforementioned packages and the "ggplot2" [30], "ggpubr" [31], "grid" [29], "Cairo" [32], "dplyr" [33], "maptools" [34], "sp" [35], and "rgdal" [36] packages.

3. Results

3.1. Spatial Variation in Forest Soil CH_4 Flux

Upland forest soil in China was a CH_4 sink with an average flux of 0.24 ± 0.02 g m^{-2} yr^{-1} (mean $\pm$ SE, positive values indicate CH_4 uptake. Negative values indicate CH_4 loss from soil to air), and values ranged from -0.83 g m^{-2} yr^{-1} to 1.79 g m^{-2} yr^{-1}. In contrast, wetland forest was a strong CH_4 source of 14.4 ± 12.81 g m^{-2} yr^{-1} (ranging from -142.18 g m^{-2} yr^{-1} to 0.25 g m^{-2} yr^{-1}), which was 60 times that of upland forest flux.

Spatial variation in the CH_4 flux of upland forest soil was observed among the different zones (Figure 2). The highest CH_4 uptake rate was observed in WTd, which was approximately two times that of the CTc, Tm, and STe zones and 1.6 and 1.8 times that of the Tg and Tr zones, respectively. The CH_4 flux of WTd was significantly higher than that of the rest of the zones ($p < 0.05$). CH_4 flux was highest between 35 and 40° N, which is the latitudinal range with the largest area of WTd. Variation in CH_4 flux with longitude was small; the CH_4 flux of all zones was similar to the mean flux.
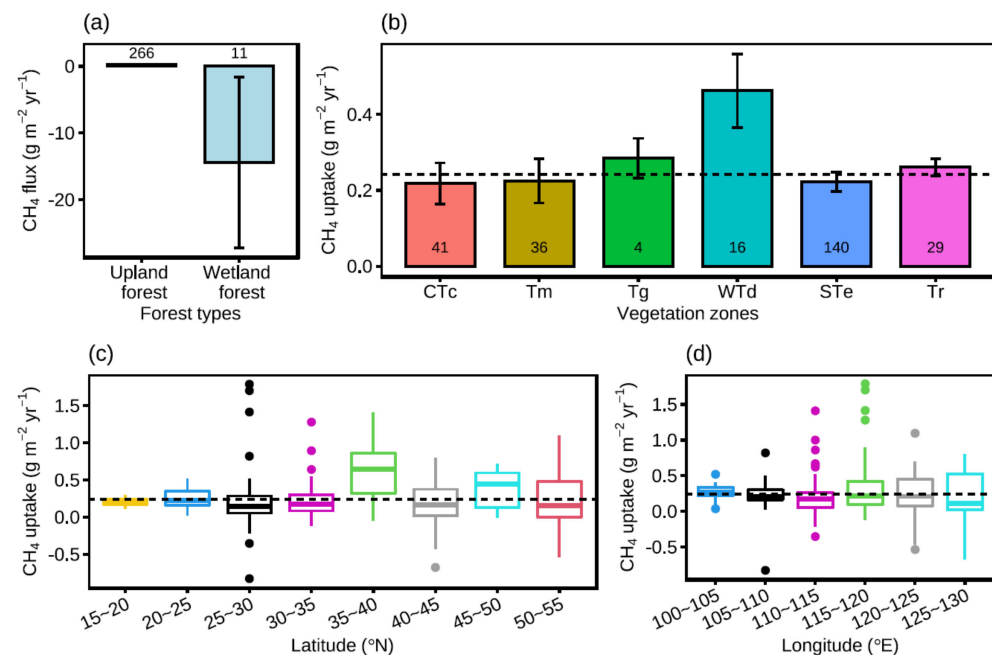
Figure 2. Spatial CH_4 flux (mean $\pm$ SE) variation of forest soil across China. (**a**) CH_4 flux of upland forest and wetland forest; (**b**) CH_4 flux of upland forest in different vegetation zones; (**c**) CH_4 flux of upland forest in different latitudinal zones; (**d**) CH_4 flux of upland forest in different longitudinal zones. The numbers above or on bars are the sample size. The dashed black line is the mean CH_4 flux of all upland forest sites. Positive values indicate CH_4 uptake and negative values indicate CH_4 loss from soil to air. See Figure 1 for the meanings of the abbreviations CTc, Tm, Tg, WTd, STd, and Tr. In (**c,d**), boxplots show 25th (Q1) and 75th (Q3) percentiles, and the horizontal lines within the boxes are the median. The whiskers are $Q1 - 1.5 \times IQR$ (interquartile range) and $Q3 + 1.5 \times IQR$. Dotes are outlier values.

3.2. Long-Term Changes in Upland Forest Soil CH_4 Uptake

The CH_4 uptake rate of upland forest soil in China varied during the 24-year study period; specifically, it decreased slightly in the first 20 years and then increased substantially (Figure 3a). Piecewise analysis showed that the break point was 2015 when data from 2007 were excluded from the analysis (2007 was the only year in which the average CH_4 uptake rate of upland forest was negative; when data from 2007 were included, 2007 was the break point. Even though upland soils were a CH_4 sink according to most observations, upland forest soil can produce CH_4 in the anaerobic center of soil aggregates or saturated zones coinciding with the water table surface [37]. Consequently, upland forest soil is a CH_4 source at the site scale in approximately 10% of all records [8]. The negative CH_4 uptake rate of 2007 might be caused by the small sample size, as only two samples were collected). The mean CH_4 uptake of the period after 2015 was significantly higher than that before 2015 ($p < 0.05$), which was 0.44 ± 0.07 g m^{-2} yr^{-1} and 0.20 ± 0.02 g m^{-2} yr^{-1}, respectively (Figure 3b).

Long-term changes were similar in CTc, Tm, Tg, and STe, although the break point varied (Figure 3c). To minimize the effect of spatial variation, we analyzed long-term variation in a typical temperate forest site in Changbai Mountain, which was the site from which data were collected over the longest period. Similar patterns of variation were observed, and an increase in CH_4 uptake was observed after approximately 2010 (Figure 3d).
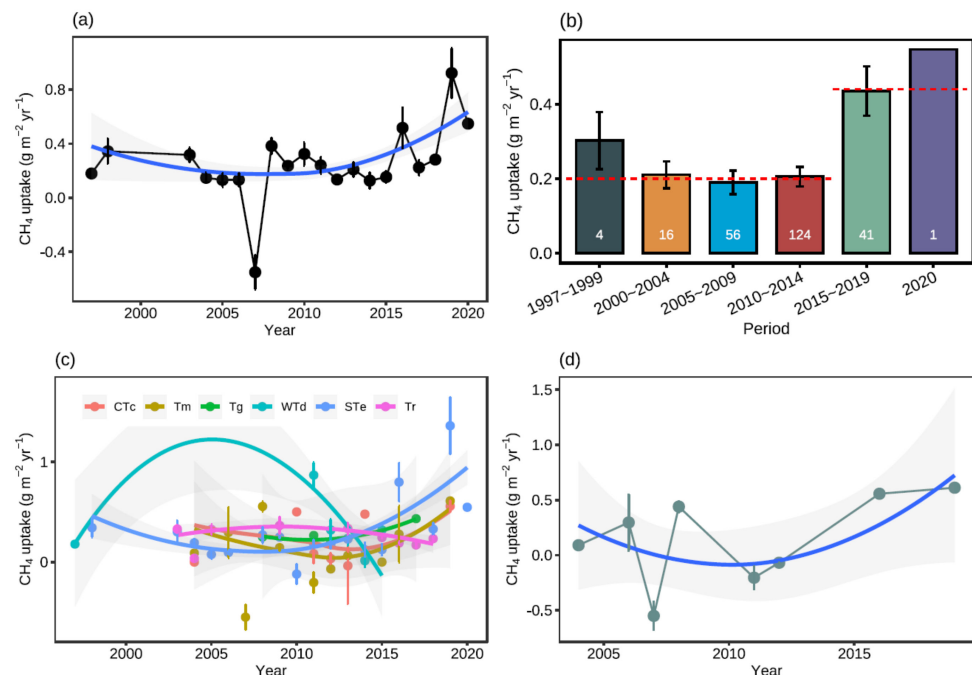
Figure 3. Long-term variation in the CH_4 uptake (mean ± SE) of upland forest soil. (**a**) CH_4 uptake variation from 1997 to 2020; (**b**) CH_4 uptake of different periods; (**c**) long-term CH_4 uptake variation of different vegetation zones; (**d**) long-term CH_4 uptake variation of typical temperate forest in Changbai Mountain. The curves in (**a**,**c**,**d**) are loess regression lines with 95% confidence intervals. Dashed lines in (**b**) are the average CH_4 uptake before and after 2015. Numbers on bars in (**b**) are sample size. The sample size for each year (**a**) in chronological order was 1, 3, 6, 10, 9, 16, 2, 15, 14, 14, 37, 33, 31, 9, 11, 8, 5, 8, 9, and 1. See Figure 1 for the meanings of the abbreviations CTc, Tm, Tg, WTd, STd, and Tr.

3.3. Relationships between Environmental Factors and CH_4 Flux

Among the 17 environmental factors, 12 of them (SWC, MAP, MAT, NH_4, POR, BD, DIN, PH, AP, AK, TN, and AN) were retained in the best random forest model, which indicates that they play an important role in explaining spatiotemporal variation in CH_4 flux. Approximately 52% of CH_4 variation can be predicted using these 12 factors (Figure 4). Among these factors, water condition was the most important parameter, followed by temperature, N deposition, and soil aeration conditions (Figure 4). SOM, TP, and TK were excluded from the best model. NO_3 was removed from the selection of predictors because of its collinearity with DIN.

AN was the only factor that was significantly correlated with CH_4 uptake variation across the six vegetation zones (Table 1). CH_4 uptake monotonically increased as AN decreased (Table 2). Negative linear correlations were observed between N deposition (DIN and NO_3, Figure 5) and CH_4 uptake. Given that CH_4 loss is maintained by CH_4 production, which is different from CH_4 oxidation, the only negative CH_4 uptake value in 2007 (see Figure 3a for details) was omitted in the correlation analysis. When this negative value was included in the correlation analysis, no significant correlations were observed between environmental variables (SWC, MAP, MAT, DIN, NH_4, and NO_3) and CH_4 flux. Partial correlation analysis at the interannual scale showed that after excluding the effect of N deposition (DIN and NO_3), the correlations between MAP/MAT/SWC and CH_4 uptake were still insignificant ($p > 0.05$).
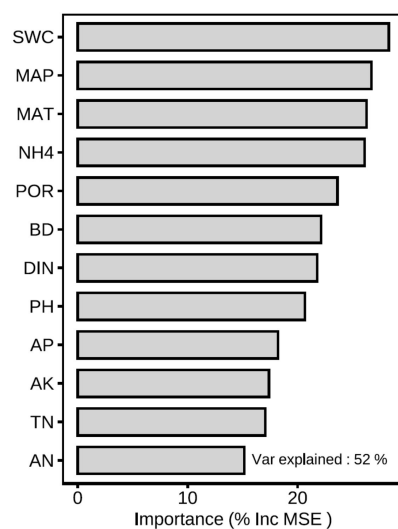
Figure 4. Importance of environmental factors in affecting upland forest soil CH_4 uptake in China. The % Inc MSE indicates the percentage increase in the mean square error when factor values were replaced by random numbers. Var explained is a measure of how much variance in CH_4 uptake is explained by the out-of-bag predictions using all 12 factors (i.e., 52% in this study). See Section 2.2 for the meanings of abbreviations.

Table 1. Spearman correlations between zonal average CH_4 uptake and environmental factors.

Environmental Factors	Correlation Coefficients	*p*-Value
MAP	−0.14	0.80
MAT	0.37	0.50
SWC	−0.26	0.66
TN	−0.49	0.36
AN	−0.94 *	0.02
AP	−0.54	0.30
AK	−0.37	0.50
PH	0.60	0.24
BD	0.01	0.92
POR	−0.31	0.56
DIN	0.26	0.66
NH_4	0.26	0.66
NO_3	0.14	0.80

* indicates significant correlations at *p* < 0.05. See Section 2.2 for the meanings of abbreviations.

Table 2. Environmental data and flux of different vegetation zones.

Parameters	All Data			Vegetation Zones					
	Max	Min	Mean ± SE	CTc (Mean ± SE)	Tm (Mean ± SE)	Tg (Mean ± SE)	WTd (Mean ± SE)	STe (Mean ± SE)	Tr (Mean ± SE)
MAP (mm)	2363.4	231.5	1095.4 ± 35.4	427.8 ± 15.3	668.3 ± 24.4	358.3 ± 54.9	571.5 ± 38.3	1398.3 ± 36.9	1711.5 ± 61.0
MAT (°C)	25.1	−6.2	11.8 ± 0.6	−5.2 ± 0.2	2.2 ± 0.2	5.0 ± 1.0	11.7 ± 0.6	17.7 ± 0.3	23.4 ± 0.2
SWC (mm)	599.9	124.3	404.1 ± 6.5	270.0 ± 5.0	376.9 ± 11.4	185.9 ± 23.4	283.2 ± 6.7	477 ± 5.2	435.7 ± 11
SOM (g/100 g)	22.7	0.7	4.4 ± 0.3	7.9 ± 0.4	5.0 ± 0.2	1.4 ± 0.4	2.7 ± 0.5	2.6 ± 0.1	2.0 ± 0.1
TN (g/100 g)	0.7	0.0	0.2 ± 0	0.4 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
AN (mg/kg)	340.3	32.6	156.4 ± 5.6	279.4 ± 11.4	241.5 ± 9.2	84.1 ± 19.2	77.2 ± 6.4	109 ± 2.3	85.3 ± 4.4
TP (g/100 g)	0.2	0.0	0.1 ± 0	0.10 ± 0.00	0.08 ± 0.00	0.06 ± 0.01	0.06 ± 0.00	0.05 ± 0.00	0.04 ± 0.00
AP (mg/kg)	11.7	1.8	5.6 ± 0.2	9.9 ± 0.4	7.8 ± 0.2	3.1 ± 0.8	4.9 ± 0.1	3.9 ± 0.1	3.2 ± 0.4
TK (g/100 g)	3.2	0.6	1.7 ± 0	2.2 ± 0.0	1.9 ± 0.0	1.9 ± 0.1	2.0 ± 0.0	1.5 ± 0.0	1.0 ± 0.0
AK (mg/kg)	196.2	33.2	104 ± 3	182.3 ± 4.6	127.8 ± 3.5	125.5 ± 21.4	94.5 ± 6.3	80.7 ± 2.3	57.4 ± 7.3
pH	8.3	4.2	5.8 ± 0.1	5.6 ± 0.1	6.0 ± 0.1	8.3 ± 0.0	7.2 ± 0.3	5.7 ± 0.1	5.2 ± 0.0
BD (g/cm^3)	1.4	0.8	1.3 ± 0	1.3 ± 0.0	1.2 ± 0.0	1.3 ± 0.1	1.4 ± 0.0	1.3 ± 0.0	1.3 ± 0.0
POR (cm^3/100 cm^3)	58.0	43.3	51.9 ± 0.2	51.8 ± 0.2	54.4 ± 0.3	52.6 ± 2.3	47.9 ± 0.6	52.1 ± 0.2	49.8 ± 0.3
GRAV (g/100 g)	25.6	0.8	10.6 ± 0.4	12.9 ± 0.7	20.6 ± 0.8	4.5 ± 0.9	11.3 ± 1.6	8.3 ± 0.5	9.4 ± 0.3
DIN (kg N ha^{-1} yr^{-1})	27.2	3.0	15.8 ± 0.5	6.6 ± 0.4	10.9 ± 0.2	13.4 ± 0.2	20.6 ± 0.9	20.3 ± 0.4	10.2 ± 0.8
NH$_4$ (kg N ha^{-1} yr^{-1})	18.9	1.1	9.4 ± 0.3	3.7 ± 0.4	5.8 ± 0.4	9.7 ± 0.4	12.1 ± 0.9	12.2 ± 0.3	5.9 ± 0.4
NO$_3$ (kg N ha^{-1} yr^{-1})	15.3	1.5	6.4 ± 0.2	2.9 ± 0.1	5 ± 0.2	3.7 ± 0.2	8.6 ± 0.2	8.1 ± 0.2	4.3 ± 0.4
CH$_4$ uptake (g m^{-2} yr^{-1})	1.79	−0.83	0.24 ± 0.02	0.22 ± 0.05	0.23 ± 0.06	0.29 ± 0.05	0.46 ± 0.10	0.22 ± 0.03	0.26 ± 0.02

Environmental parameters are average values of the CH$_4$ flux sampling points, not the average of entire vegetation zones. See Section 2.2 and Figure 1 for the meanings of abbreviations.
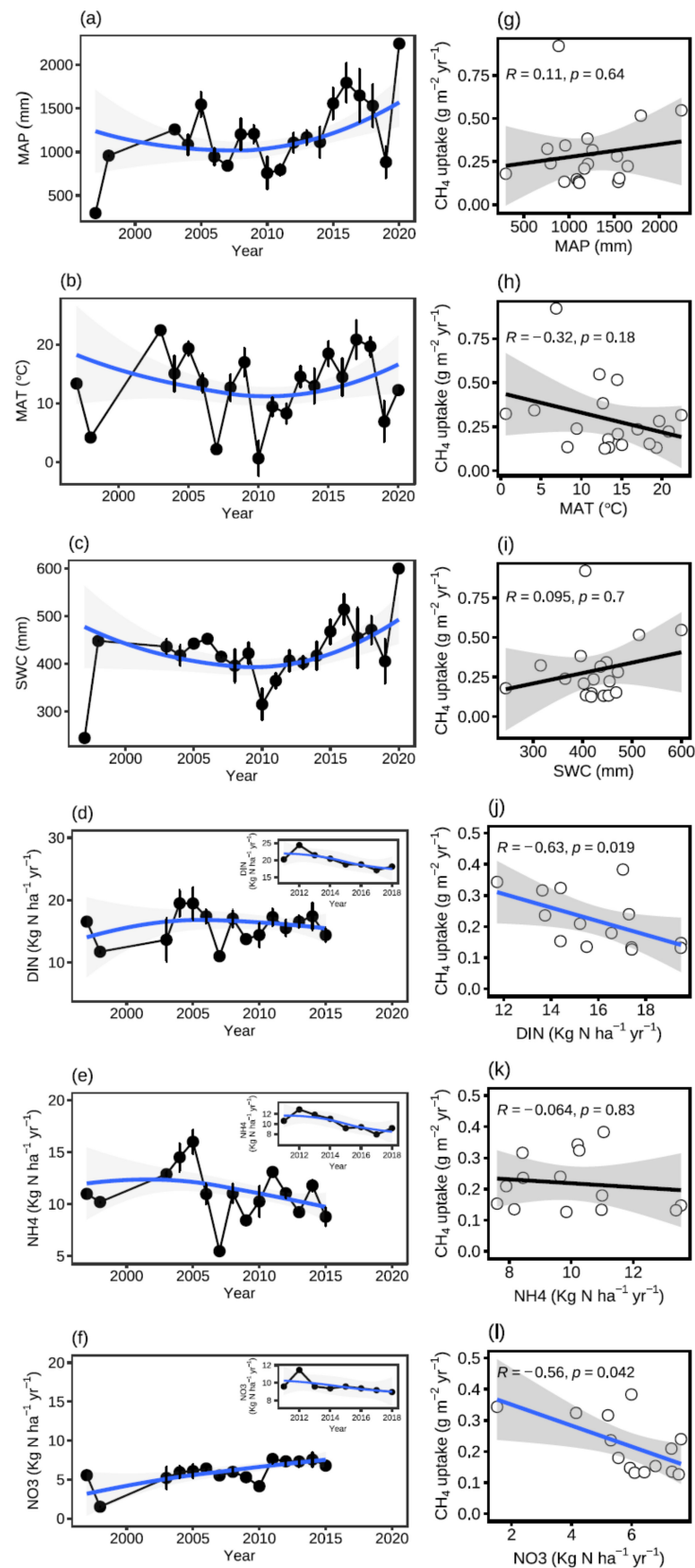
Figure 5. Interannual environmental variation and relationships among CH_4 uptake and environmental factors at the interannual scale. (**a–f**) Interannual variation of environmental factors; (**g–l**) Relationships among CH_4 uptake and environmental factors at the interannual scale. The curves in

(**a**–**f**) are loess regression lines with 95% confidence intervals. Regional N deposition data were not available after 2015. The national average N deposition of China from 2011 to 2018 [38] is shown in small plots on the right of (**d**–**f**) to provide information on the change of N deposition after 2015. These data are not included in correlation analysis. *R* and *p* in (**g**–**l**) denote correlation coefficients and *p*-values, respectively. Linear regression lines with 95% confidence intervals are shown. CH_4 uptake and environmental parameters were averaged by years. One negative flux value was omitted from the analysis, and no significant correlations were observed between CH_4 flux and the six factors when this negative value was included. See Section 2.2 for the meanings of abbreviations.

4. Discussion

4.1. Upland Forest Soil in China Is an Important CH_4 Sink

Forest soil is widely recognized as an important CH_4 sink. The mean CH_4 uptake of forest soil in China based on in situ observational data was 0.24 ± 0.02 g m^{-2} yr^{-1}, which is lower than that reported by a previous study (0.43 g m^{-2} yr^{-1}) [12] but similar to that reported by a recent study [8]. The mean uptake rate in our study was in the range of global mean CH_4 uptake values reported by different studies (i.e., from 0.19 to 0.61 g m^{-2} yr^{-1}) [3,8,12,14,15]. Forest is the largest terrestrial carbon sink. The net ecosystem productivity (NEP) of Asian forest is 645.3 g CO_2 m^{-2} yr^{-1} [39]. Given that the global warming potential of CH_4 is 81 times that of CO_2 over a 20-year period (GWP$_{20}$) [1], CH_4 uptake could enhance the climate change mitigation effect of upland forest by approximately 3%. This percentage in low or high latitudinal areas could be several times higher, such as 8% from 10° N to 20° N and 10% from 50° N to 60° N (calculated based on data from our study and data from Yu et al. (2014)).

The CH_4 uptake rate of WTd was significantly higher than that of the other five vegetation zones (Figure 2). Soil AN was the only environmental parameter significantly correlated with CH_4 uptake (Table 1). The average soil AN of WTd was the lowest among the different vegetation zones (Table 2). Soil AN is composed of inorganic N (mainly consisting of NH_4^+ and NO_3^-) and easily hydrolyzed organic nitrogen (including amino acids, amides, and easily hydrolyzed proteins). Negative relationships between the soil N content and CH_4 uptake have been widely reported [40,41]. Soil N inhibits CH_4 uptake through mechanisms such as competition of NH_4^+ with CH_4 monooxygenase because of their similar molecular structure, the toxic effects of NO_3^- on methanotrophic bacteria, and the enrichment of AN, which increases litter accumulation on the soil surface and indirectly inhibits soil CH_4 uptake by reducing the diffusion of CH_4 and O_2 at the air–soil interface [42–46].

Water conditions and temperature might also contribute to explaining variation in the CH_4 uptake rate among regions. The precipitation of WTd was relatively moderate (average of 571.5 mm per year at all sites located in the area, Table 2) compared with that of STe and Tr (averages of 1398.3 mm and 1711.5 mm, respectively) and Tg (average of 358.3 mm). In general, variation in CH_4 uptake tends to first increase and then decrease as the soil water content increases [47]. Precipitation addition has been shown to decrease CH_4 uptake in a temperate forest that receives ambient rainfall of 1400 mm per year [48]; precipitation addition has also been shown to increase CH_4 uptake in a temperate desert steppe that receives 150 mm of rainfall per year [49]. High precipitation may result in decreases in net CH_4 uptake by inhibiting CH_4 oxidation or accelerating CH_4 production, which prolongs soil anaerobic conditions [50]. Inadequate precipitation can also weaken CH_4 uptake because methanotroph activity decreases under drought stress, although methanotrophs prefer aerobic soil conditions [51]. The annual precipitation of CTc and Tm is similar to that of WTd, but the CH_4 uptake of CTc and Tm is lower than that of WTd. Continuous permafrost, island permafrost, and seasonal frozen soil are present in CTc and Tm [52]. The frozen soil can form a barrier that prevents rainwater from leaking, which can cause more water to accumulate in the near surface soil and reduce CH_4 uptake. In addition, the lower CH_4 uptake rate might be partly explained by the lower annual mean temperature of CTc and Tm compared with WTd (-5.2 °C, 2.2 °C, and 11.7 °C, respectively,

Table 2). In short, the higher CH_4 uptake of WTd might be explained by the low soil N and moderate water conditions, but more direct evidence is needed to confirm this conclusion.

The CH_4 emission rate of wetland forests is high. The average emission velocity was 14.40 ± 12.81 g m^{-2} yr^{-1}, and the highest value in our dataset was 142.18 g m^{-2} yr^{-1}. This is comparable to other types of wetlands, such as mangroves, swamps, and water bodies [53–56]. Nevertheless, our findings were inconsistent with the results of a study of global forest CH_4 flux that found that the CH_4 flux of upland forest and wetland forest is similar [8]. Additional studies at the site and regional scale are needed to improve the robustness of CH_4 flux estimates of wetland forest as well as resolve discrepancies among studies. The CH_4 emissions of wetland forest are 60 times the CH_4 uptake of upland forest. Mean CH_4 emissions are nearly two times the NEP when GWP_{20} is considered. Freshwater swamp forest accounts for 1.4% of the total forest area of the globe [57], which suggests that wetland forest might offset 84% of the CH_4 uptake by upland forest, albeit much uncertainty in the exact figures remains. Regional CH_4 emissions of inland wetland forest are seldom mentioned in previous studies of CH_4 emissions of forests and wetlands [3,58,59]. The high level of CH_4 emissions estimated suggests that there might be considerable bias in estimates of ecosystem greenhouse gas budgets, which might be derived from a lack of knowledge of inland wetland forest CH_4 emissions.

4.2. CH₄ Uptake of Upland Forest Soil Is Increasing

To explore interannual variation in CH_4 uptake and the response of CH_4 uptake to global change, long-term variation in CH_4 uptake and typical global change parameters, i.e., precipitation, temperature, and atmospheric N deposition, was investigated. Over the past two decades, the CH_4 uptake of upland forest soil in China decreased until 2015 (Figure 3). This finding is consistent with the results of a previous study indicating that the global CH_4 uptake by forest soil decreased from 1988 to 2015 [13]. However, CH_4 uptake increased dramatically after 2015, and it was significantly higher than before 2015 (Figure 3).

Patterns of DIN and NO_3 were opposite those of CH_4 uptake, and significant negative correlations were observed at the interannual scale (Figure 5). In light of the correlation between regional soil AN and CH_4 uptake, the negative correlations between N input and CH_4 uptake indicate that N plays an important role in regulating CH_4 flux. Since the 1990s, China has taken several actions to improve air quality, such as "Reducing the use of N fertilizer and improving N use efficiency", "Air Pollution Prevention and Control Action Plan", and "Action plan for zero growth in fertilizer use by 2020". These measures have induced substantial declines in N deposition since 2000 [38,60]. Nitrogen addition experiments have been conducted to clarify the effect of N on terrestrial CH_4 flux [61–63]. Although the amount of N deposition was generally moderate compared with the amount input in the N addition experiments, our results confirmed the effects of N deposition on the CH_4 uptake of forest soil across interannual scales. Our findings indicate that the CH_4 fixation of upland forest soil will play an increasingly larger role in climate change mitigation in the coming decades as new and long-lasting measures were initiated in 2020 to achieve China's goals of having emissions peak before 2030 and reaching carbon neutrality by 2060. Improvements in energy efficiency and pollution reduction are the most important pathways for meeting these targets [64].

Briefly, the interannual pattern of MAP, SWC, and MAT was the same as that of CH_4 uptake (Figure 5), which might partly explain interannual variation in CH_4 uptake. Soil water conditions are one of the most important variables affecting CH_4 flux through its effects on CH_4 consumption and production [8,14]. Temperature also has a major effect on microbial activity [65]. However, Spearman correlation analysis and partial correlation analysis (excluding the effect of N deposition) of the two decades of data revealed insignificant relationships between water conditions/temperature and CH_4 uptake. The weak correlations observed in the present study might be caused by interactions with other environmental factors, especially biotic factors that were not analyzed in the present study

owing to the difficulty of obtaining data across a large region (e.g., community composition of methanotrophs, amount of competitive microbes, interactions with plant metabolic processes, etc. [8,66]), variation in the response of CH_4 uptake to water conditions and temperature across years triggered by shifts in dominant environmental limitations and adaptation to long-term environment change [67–69], or bias caused by variation in the number of samples among years. Air temperature and precipitation in China have been increasing from 1961 to 2020 and are expected to continue to increase in the near future [70]. Our findings also suggest that the CH_4 uptake of forest soil in China might continue to increase in the following years, but there remains a great deal of uncertainty regarding future patterns.

5. Conclusions

Upland forest soil in China is an important CH_4 sink. Soil N conditions and atmospheric N deposition significantly inhibit CH_4 uptake. For the first time, we found that long-term variation patterns of N deposition were opposite those of CH_4 uptake on regional scale of China. Given that China aims to achieve carbon neutrality in the coming decades, declines in N deposition might increase the CH_4 uptake of upland forest soil. Precipitation and temperature are important factors affecting the soil CH_4 sink, but long-term response patterns of CH_4 uptake to precipitation and temperature were not clear. To support decision-making on climate change mitigation, more studies are needed to explore the responses of soil CH_4 uptake to climate change, anthropogenic activities, and their interactions.

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