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A Global Database of Soil Methane uptake (SMUD)

Jiawei Jiang[1], Zhifeng Yan[1,2*], Jinshi Jian[3,4*], Jesper Riis Christiansen[5], Xinchu Wang[1,2], Ren-Min Yang[1], Zhen Zhang[6], Philippe Ciais[7]

[1]Institute of Surface-Earth System Science, School of Earth System Science, Tianjin University, Tianjin 300072, China.
[2]Tianjin Bohai Rim Coastal Earth Critical Zone National Observation and Research Station, Tianjin University, Tianjin 300072, China.
[3]State Key Laboratory of Soil and Water Conservation and Desertification Control, College of Soil and Water Conservation Science and Engineering, Yangling District, Xianyang 712100, China.
[4]Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, 26 Xinong Road, Yangling District, Xianyang 712100, China.
[5]Department of Geoscience and Natural Resource Management, University of Copenhagen, Frederiksberg, DK 1958, Denmark
[6]National Tibetan Plateau Data Center (TPDC), State Key Laboratory of Tibetan Plateau Earth System, Environment and Resource (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, 100101, China
[7]Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, 91190, Gif sur Yvette, France.

Corresponding to： Zhifeng Yan (yanzf17@tju.edu.cn) and Jinshi Jian (jinshi@nwafu.edu.cn)

Abstract

Soil methane uptake (SMU), the second-largest and represents a biologically mediated sink for atmospheric methane (CH_4) in terrestrial ecosystems, plays a non-negligible role in regulating the global CH_4 budget. Field SMU observations have been conducted since the 1980s, but have not yet been systematically compiled within any unified and openly available framework. Here, we present the global Soil Methane Uptake Database (SMUD), which includes 2427 site-level records from 920 peer-reviewed publications spanning 1986 to 2025. SMUD contains SMU measurements at multiple temporal scales, including daily (n = 1425), monthly (n = 2001), seasonal (n = 1720), and annual (n = 1098), along with soil moisture and temperature data at daily and monthly scales. The collected datasets cover all major climatic zones and ecosystem types, across which SMU exhibits pronounced spatial and temporal variability. We found that seasonal- and biome-specific variations were key to understanding intra-annual changes in SMU. In particular, the effects of soil temperature and moisture on SMU are biome-specific: observations from Temperate Grassland are primarily associated with temperature changes, whereas those from Tropical Rainforest and Desert are mainly controlled by moisture, and other biomes show a mix of controlling factors. Overall, SMUD provides a comprehensive basis for understanding the global patterns of SMU, unraveling the underlying mechanisms, and

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estimating the global SMU budget. The database, associated data, and code to reproduce the results can be found at https://doi.org/10.5281/zenodo.18299391 (Jiang et al., 2026). We aim to establish SMUD maintenance as a collaborative, community-driven, shared, and user-managed database within the research community.

1 Introduction

1.1 The critical role of soil methane uptake (SMU) in the global methane cycle and its broader impacts

Among the three major long-lived GHGs, methane (CH_4) has contributed up to around 0.5°C of warming and accounts for approximately 30% of observed global warming (Masson-Delmotte et al., 2021; Shindell et al., 2012). On a per-unit basis, CH_4 exerts a more potent warming impact than carbon dioxide (CO_2) over short timescales due to its higher radiative efficiency (Saunois et al., 2025). Since the Industrial Revolution, the persistent increase in atmospheric CH_4 reflects a sustained imbalance between its emissions and sinks (Gauci et al., 2024). CH_4 mitigation has thus become a central focus of international climate targets, with the Global Methane Pledge targeting a ≥30% reduction in anthropogenic CH_4 emissions by 2030 relative to 2020 (Saunois et al., 2025). In this context, a comprehensive understanding of both anthropogenic sources and natural sinks is required to assess the net CH_4 budget and mitigation potential. Consequently, accurately characterizing the magnitude and spatial-temporal patterns of the current and future soil CH_4 sink is critical for effective mitigation strategies (Saunois et al., 2025).

Soils are key environments for CH_4 cycling, where CH_4 is consumed by aerobic methanotrophs and generated by anaerobic methanogens; consequently, the net flux is controlled by a complex interplay among various factors regulating soil methanotroph and methanogen activity (Ni and Groffman, 2018; Bridgham et al., 2013). Soil methane uptake (SMU) represents the second-largest sink of atmospheric CH_4 and is the only clearly identified biologically mediated oxidative sink within terrestrial ecosystems through microbial oxidation of atmospheric CH_4 (Song et al., 2024; Saunois et al., 2025). However, human land-use change has profoundly impaired this sink (Smith et al., 2000). For example, without the widespread conversion of natural ecosystems to croplands since the mid-19th century, SMU in temperate regions would likely be higher by up to a factor of three, at 27 Tg CH_4 yr^{-1} instead of 8 Tg CH_4 yr^{-1} (Ojima et al., 1993; Tate, 2015). Given that the global atmospheric CH_4 burden is growing at approximately 19.0–36.0 Tg CH_4 yr^{-1} in this century, enhancing SMU thus represents a potential strategy to partially offset or mitigate this increase (Saunois et al., 2025). Moreover, SMU represents a potentially manageable terrestrial CH_4 sink, as it can be directly influenced by human activities that alter soil properties and land uses (De Bernardi et al., 2022).

Global SMU remains highly uncertain, with bottom-up estimates ranging from 11 to 49 Tg CH_4 yr^{-1} (Saunois et al., 2025). This uncertainty is largely attributable to the substantial temporal and spatial variability of SMU (Jiang et al., 2025). Temporally, continuous measurements have revealed large fluctuations, with interannual variability reaching up to

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163.2% (Luo et al., 2012). Intra-annual variability is also pronounced, with distinct seasonal patterns observed across diverse climate zones and ecosystems (Luo et al., 2013). Spatially, SMU exhibits considerable heterogeneity across latitudes (Murguia-Flores et al., 2018) and among biomes (Jiang et al., 2025). These spatial differences are largely driven by variations in environmental conditions and management practices, which introduce substantial uncertainty in estimating global SMU (Song et al., 2024). Global SMU estimates rely on data-driven and process-based approaches. Data-driven methods aggregate observations by ecosystem or climate but are limited by data bias and coarse spatial representation. Process-based models simulate grid-scale SMU using CH_4 oxidation and diffusion processes, yet commonly assume invariant parameters inconsistent with observations, resulting in divergent estimates (Jiang et al., 2025).

1.2 The need for a unified SMU database

Many field experiments have been conducted since the 1980s to measure SMU across a wide range of climatic conditions and ecosystems (see Supplementary file "CH4 uptake data_CH4 FLUX_1_1410", Fig. 1). However, most existing SMU estimates rely on small-scale, site-specific observations, which are fragmented and unsystematic due to diverse measurement units and the absence of standardized approaches across research groups. Therefore, standardizing and integrating past SMU measurements into a coherent data framework is essential for supporting synthesis studies and advancing global CH_4 research.

Several databases have been developed based on in situ measurements to support global SMU estimates since 2000 (Jiang et al., 2025). However, these databases lack comprehensive representation of different ecosystems and climatic zones, and are insufficient to capture spatiotemporal variability due to data scarcity. For example, Grosso et al. (2000) focused exclusively on Europe and North America observations rather than providing a global assessment, whereas Dutaur et al. (2007) presented a global estimate that was nevertheless dominated by data from Europe and North America; similarly, although Murguia-Flores et al. (2018) reported global estimates, their analysis was based on a highly limited database comprising only about 100 observations from roughly 30 studies.

Although the count of measurements has grown over time, existing databases are still inadequate to robustly estimate global SMU. Most global SMU estimates have been derived from low temporal resolution data and primarily annual averages, which overlook essential intra-annual variability (Li et al., 2025). In addition, many previous estimates used simplified ecosystem classifications (Li et al., 2025) or focused on a single ecosystem type (Ni and Groffman, 2018), limiting their usefulness for comprehensive syntheses of global SMU estimates.

Consequently, obtaining comprehensive and accurate global SMU measurements, coupled with associated soil physicochemical properties that can be used to generalize and upscale existing observations, is essential for improving the reliability of SMU estimates. Additionally, such a database would facilitate further research into linking and modeling key soil biogeochemical (Aronson and Helliker, 2010) and plant biological processes (Voigt et al., 2023; Chai et al., 2020) that regulate SMU, as well as modelling how SMU responds to dynamic and changing environmental conditions (Song et al., 2024; Murguia-Flores et al., 2018).

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Our primary aim is to harmonize disparate data sources, standardize measurement units, ensure complete metadata, and integrate global SMU observations to construct a comprehensive database across different temporal and spatial scales. We also aim to provide a robust and open platform that facilitates advanced research and enhances the modeling and prediction of CH_4 dynamics under varying climatic and environmental conditions. Furthermore, we hope to foster collaboration and knowledge exchange within the scientific community, ultimately informing policy decisions and mitigation strategies to address increasing atmospheric CH_4 concentrations and their implications for climate change.

2 Methods

2.1 Database Compilation

All available studies reporting SMU were compiled from peer-reviewed publications through a systematic search in databases: Web of Science (https://clarivate.com.cn/solutions/web-of-science/) and the China National Knowledge Infrastructure (CNKI, http://www.cnki.net/). The search covered peer-reviewed articles published between 1986 and 2025, and the search strategy used Boolean logic with the following items: TI = (CH_4 OR methane OR greenhouse gas) AND TS = (soil AND (*flux OR oxidat* OR uptake OR consumption OR exchange OR sink)). The title, abstract, figures, and tables of each study were used to decide whether to include it. In total, almost 10040 papers were retrieved.

Studies were considered eligible if they met the following criteria: (i) the study reported in situ field measurements of SMU; laboratory incubation experiments and purely modeling-based studies without field observation were excluded; (ii) the control group without amendment was selected when multiple treatments were applied; (iii) at least one of the following types of SMU data was reported: mean annual, seasonal, monthly, weekly, or daily values; measurements at the hourly scale within a single day were excluded. The flux data in SMUD were organized into three categories based on temporal aggregation: Monthly, Seasonal, and Annual (see Supplementary file "Studies and Fluxes"). In total, 920 papers met these criteria, with about 84% (773) from the Web of Science and the rest from CNKI (Fig. 1). SMU data were provided by the authors or extracted by digitizing graphs in the papers using the GetData Graph Digitizer (version 2.26, http://www.getdata-graph-digitizer.com/) when data were presented in the graphs. Seasonal and annual values were aggregated from shorter timescale fluxes when not provided in the original publication. Additional site information, including location (latitude, longitude, elevation, country, and region), climate conditions, and ecosystem types (e.g., forest, grassland, and agriculture) was collected (see Table 1 and Supplementary file "Studies and Fluxes"). Mean annual temperature (MAT) and mean annual precipitation (MAP) were acquired from ERA5-Land Monthly Aggregated data (Fig. S1, doi:10.24381/cds.68d2bb30). When latitude, longitude, and elevation were missing, we supplemented it using Google Earth (https://earth.google.com/) based on the original site description.

The data were categorized according to biomes in the Whittaker biome diagram (Fig. 2) comprising Tundra (Tun), Boreal Forest (BF), Temperate Seasonal Forest (TSF), Temperate Rainforest (TRF), Temperate Grassland (TG), Desert (Des), Tropical Rainforest (TRRF),

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Tropical Seasonal Forest (TRSF), Savanna (Sav), Subtropical Desert (SDes), Woodland (Wood), and Shrubland (Shrub). Observations outside the Whittaker biome framework were reclassified into Alpine (Alp), Agriculture (Agri), Bare, Urban, and Others, with the last of these comprising data from special sources (e.g., saline–saline-alkaline soils, blanket peats, landfills, wetlands, riparian, floodplain, ant nests, and atmosphere-soil-cave systems).

2.2 Database structure

SMUD consists of two separate Supplementary files. The “Studies and Fluxes” file (Table 1) contains publication information, site-specific metadata (e.g., location, climatic conditions, and ecosystem type), and experimental details, including sampling time, duration, frequency, and measurement methods. This file also includes monthly, seasonal, and annual SMU fluxes as reported by the authors or calculated from raw data. The second file, named “CH4 uptake data_CH4 FLUX_1_1410”, contains the acquired daily and monthly SMU measurements (Table 2). Each record includes information on the sampling year, day of year (DOY), and corresponding SMU fluxes. An index number (paper-study ID) maps entries between these two files.

SMU units in the “CH4 uptake data_CH4 FLUX_1_1410” file follow the original units reported in the source publications and are composed of four components: gas species, mass, area, and time. All SMU values were converted to μg CH_4-C m^{-2} yr^{-1}. The calculation of CO_2-equivalents of CH_4 used a factor of 27.2 (i.e., Global Warming Potential of CH_4 relative to CO_2 over a 100-year period) (Masson-Delmotte et al., 2021). The “Studies and Fluxes” file contains 66 fields (Table 1), whereas the “CH4 uptake data_CH4 FLUX_1_1410” file contains 6 fields (Table 2). Both files are provided in comma-separated values (CSV) format that can be read by most standard data-processing software.

Table 1. Categories of database fields and corresponding descriptions for the Supplementary file “Studies and Fluxes”.

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Num	Field name	Unit	Description
		Metadata	
1	Paper_number	-	Paper number
2	Study_number	-	Study number
3	Paper_title	-	Paper Title
4	Paper_author	-	The name of the first author
5	Paper_year	-	The year the paper was published
6	Paper_journal	-	Journal of Publication
7	Paper_language	-	English or Chinese
8	Entry_date	-	Entry date
9	Collector	-	Data collector
10	Checker	-	Data checker
		Site and condition	
11	Continent	-	Continent
12	Country	-	Country
13	Region	-	State/province/region
14	Site_name	-	Name of study site
15	Study_duration	month	Duration of measurement
16	Study_frequence	per month	frequency of measurement
17	Flux_method	-	Flux measurement method: Static chamber; Eddy covariance
18	CH_4_method	-	CH_4 concentration analysis technique: Gas chromatograph, Laser spectroscopy
19	Latitude	-	Latitude, decimal; positive = North, negative = South
20	Longitude	-	Longitude, decimal; positive = East, negative = West
21	Elevation	m	Elevation
22	MAT	°C	Reported mean annual temperature
23	MAP	mm	Reported mean annual precipitation
24	Climate	-	Climate zones of sites
25	Ecosystem	-	Ecosystems of sites
26	Biome	-	Biomes are categorized according to the Whittaker biome diagram (see Methods)
		Annual, seasonal, and monthly SMU	
27-37	SMU Jan to Dec	μg CH_4-C m^{-2} h^{-1}	Monthly SMU flux
38-41	SMU Spr to Win	μg CH_4-C m^{-2} h^{-1}	Seasonal SMU flux
42	annual	μg CH_4-C m^{-2} h^{-1}	Annual SMU flux
		Soil moisture (SM) and soil temperature (ST)	
43-55	SM Jan to Dec	WFPS (%)	Monthly mean soil moisture at topsoil

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56-66	ST Jan to Dec	°C	Monthly mean soil temperature at topsoil

Table 2. Categories of database fields and corresponding descriptions for the Supplementary file "CH4 uptake data_CH4 FLUX_1_1410".

Num	Field name	Unit	Description
1	Paper_number	-	Paper number
2	Study_number	-	Study number
3	Meas_year	-	The year the study was performed
4	Meas_mark	-	This field was used to separate different sub-records (e.g., layers or treatments) reported within the same paper, study, and year; these sub-records were then averaged.
5	DOY	-	A single number is used to denote the day of year
6	Fluxes	Given by the original papers	Corresponding observation fluxes

2.3 Quality control

A basic quality-control procedure was applied to the database, and quality flags (Q01-Q07) were used to identify entries with known issues or potential problems. We gave preference to data directly reported by the authors, under the assumption that such data were of higher quality than those calculated or extracted from figures or tables. Incubation data (Q01) and duplicate records (Q02) were excluded. The specific sampling time was recorded to ensure accurate documentation of SMU variability at fine temporal scales, which can influence monthly, seasonal, and annual estimates. When the exact sampling time was not reported, the corresponding records were flagged in Q03 and classified into the "Other" category (Supplementary file "Studies and Fluxes"). Incorrect units often result in outliers; therefore, both confirmed and suspected unit errors were identified based on unit conversion results, as well as information from figures, tables, and surrounding text (Q04). Data with erroneous flux units in the original publication were excluded from the analysis. Coordinate projections in Google Earth (https://earth.google.com/) were used to identify and correct inaccurately reported site locations (Q05). For records lacking coordinate information, geographic coordinates were supplied based on the descriptions of local plots. Despite these efforts, some errors persisted; therefore, records annotated as "other known problem with data" were systematically flagged to alert users to potential issues (Q06). In addition, we identified and marked the daily-scale data (Q07).

2.4 Data analysis

In this study, the consistency between study-reported MAT/MAP and ERA5-Land–derived

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MAT/MAP was assessed by sampling ERA5-Land at site coordinates (0.1°) and fitting linear regressions (ERA5 vs. original). Regression slope, intercept, R^2, and N are reported, with the 1:1 line shown as a reference (Fig. S1). ERA5-Land–derived MAT and MAP show strong agreement with study-reported values (MAT: $R^2 = 0.86$, slope = 0.898; MAP: $R^2 = 0.79$, slope = 0.781). SMU values were obtained in two ways: directly from the literature or by computation. Monthly SMU fluxes (Jan–Dec) were derived as arithmetic means of daily fluxes within the corresponding DOY ranges for each observation. Seasons were defined as follows: spring (March-May in the Northern Hemisphere and September-November in the Southern Hemisphere), summer (June-August in the Northern Hemisphere and December-February of the following year in the Southern Hemisphere), autumn (September-November in the Northern Hemisphere and March-May in the Southern Hemisphere), and winter (December-February of the following year in the Northern Hemisphere and June-August in the Southern Hemisphere). Seasonal fluxes were calculated only if data were available for all months within the corresponding season. Annual values were calculated when field measurements covered a full 12-month period and included values for all four seasons (or for paired seasons such as growing vs. dormant or wet vs. dry). All SMU values were expressed in or converted to units of μg CH_4-C m^{-2} h^{-1}. CH_4 uptake was defined as positive, and only uptake observations were used in subsequent analyses. Monthly soil moisture and soil temperature were also calculated from daily observations according to DOY. Soil moisture was expressed as water-filled pore space (WFPS). If WFPS was not reported, its value was calculated based on the reported volumetric (θ_v, m^3 m^{-3}) or gravimetric (θ_g, g g^{-1}) soil moisture as follows (Borken et al., 2006):

$$WFPS = \theta_v/(1 - BD/2.65) = \theta_g \times BD/(1 - BD/2.65) \qquad (1)$$

where *BD* is bulk density (g cm^{-3}); when *BD* was not reported, it was retrieved from SoilGrids250m 2.0 (Poggio et al., 2021). All the data were organized and archived in Microsoft Excel (see Supplementary files "Studies and Fluxes" and "CH4 uptake data_CH4 FLUX_1_1410"). We used the *coefficient of variation (CV)* to express the amplitude of the SMU variation within a year:

$$\sigma = \sqrt{\textstyle\sum_{i=1}^{N}(x_i - \mu)^2/N} \qquad (2)$$

$$CV = (\sigma/\mu) \cdot 100\% \qquad (3)$$

where σ is standard deviation, x_i is the i-th observation, μ is sample mean, and N is the sample size. *CV* was classified as low ($CV < 10$ %), medium (10 % $\leqslant CV < 20$ %), high (20 % $\leqslant CV < 30$ %), and very high ($CV \geqslant 30$ %) (Vaz et al., 2017; Mashalaba et al., 2020).

All calculations were performed using MATLAB code (MATLAB code files 1-3), and all figures were drawn using R (code files 1-11). Analyses were conducted using R version 4.5.0 (R Core Team 2025).

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3 Results and discussion

3.1 Overview of the SMUD

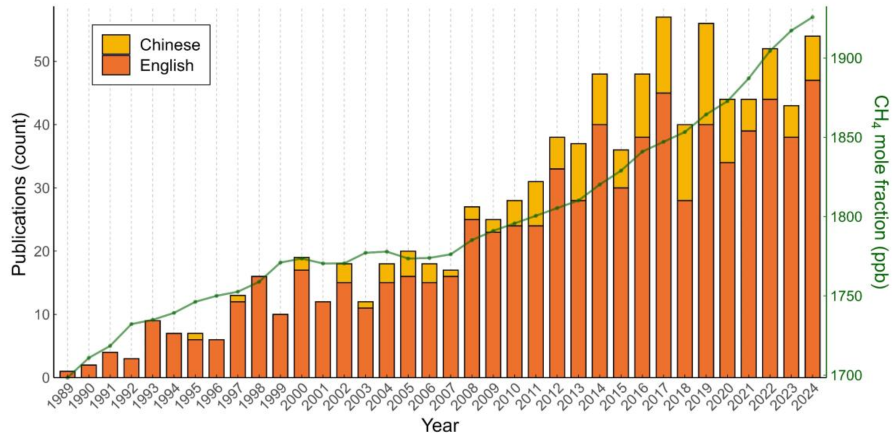

Figure 1. Peer-reviewed publications on soil methane uptake over time, from the Web of Science and CNKI databases. The green line indicates the globally averaged atmospheric CH_4 concentration (adapted from https://gml.noaa.gov/ccgg/trends_ch4/).

The current database includes 2427 site-level records from 914 sites extracted from 1048 peer-reviewed publications, spanning publication years from 1986 to 2025 and covering measurement years from April 1983 to November 2023. The majority of publications (approximately 84%) are in English, with the remainder published in Chinese. The dataset comprises 1425 daily-scale measurements from 681 sites, 2001 monthly-scale measurements from 973 sites, 1720 seasonal-scale measurements from 795 sites, and 1098 annual-scale measurements from 535 sites.

The number of studies has gradually increased since the 1980s, with a pronounced surge over the past two decades. The expansion of SMU studies is closely linked to advances in CH_4 measurement techniques: detection methods have evolved from laboratory wet-chemical analysis to automated chromatography, laser spectroscopy, and further to satellite remote sensing and intelligent monitoring, forming a multi-scale and comprehensive monitoring system (Baldocchi, 2003; Jacob et al., 2016; Werle et al., 1993; Crosson, 2008; Khalil et al., 1989). Moreover, the pattern appears to align with shifts in atmospheric CH_4 over the last 40 years: following a relatively steady period, CH_4 levels began to rise again around 2007 (Reay et al., 2018). One possible interpretation is that the renewed increase in atmospheric CH_4 has helped draw more attention to SMU.

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3.2 Spatial distribution of data

The database has broad spatial coverage and encompasses most key regions where SMU studies have been conducted (Fig. 2). The most frequently represented countries include China (n = 761 records, hereafter "n =" was omitted), the United States (320), Germany (139), Japan (131), Canada (121), Finland (90), Australia (80), Brazil (71), Indonesia (52) and the United Kingdom (51). Across continents, Asia contributed 43.0% of all records (1023), followed by Europe (22.7%, n = 540, hereafter "n =" was omitted), North and Central America (21.0%, 499), South America (5.1%, 122), Oceania (4.1%, 97), Africa (3.5%, 84), and Antarctica (0.7%, 16). These results indicate a strong sampling bias toward observations from the Northern Hemisphere. Records are primarily concentrated in eastern Asia, North America, and Europe. In contrast, large areas of Oceania, Africa, and the polar regions have substantially fewer measurements (Fig. 2).

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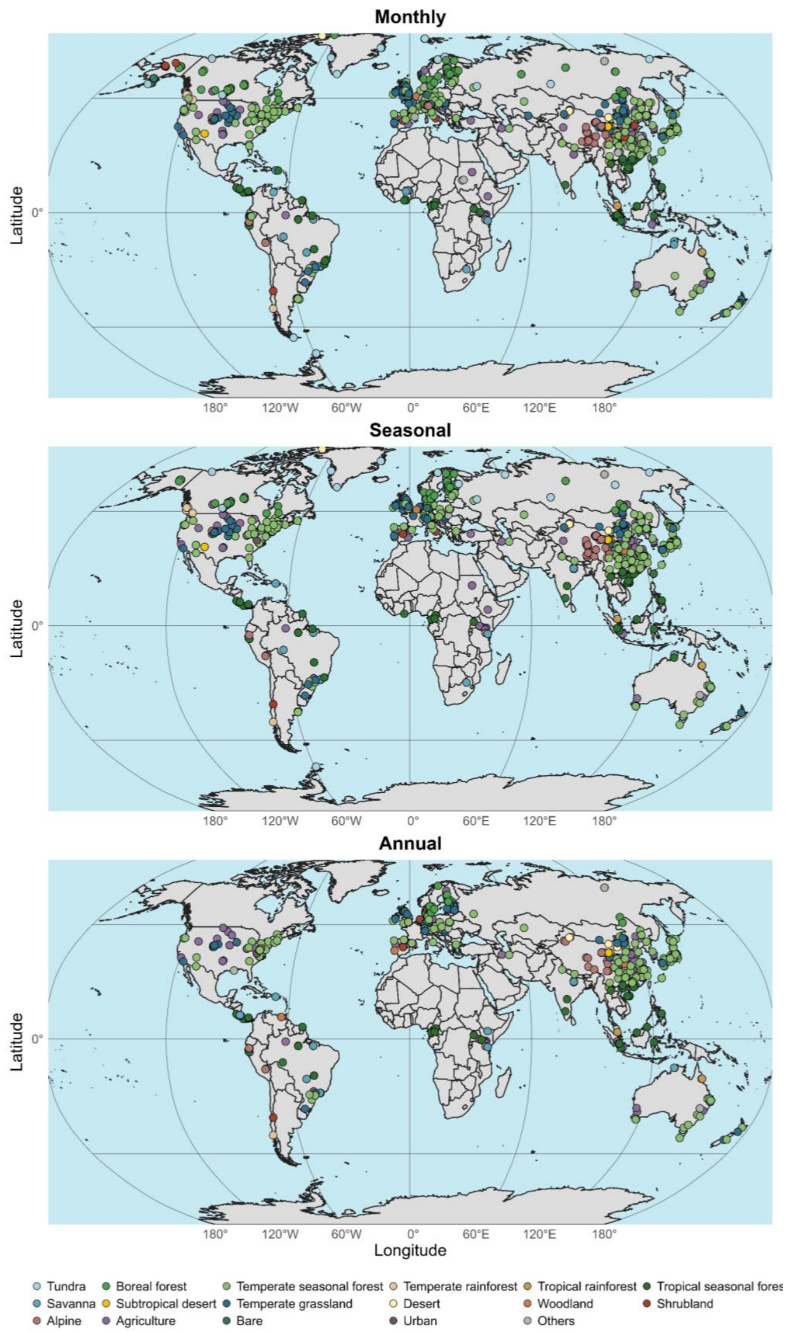

Figure 2. Geographic distribution of global SMU measurement sites across biomes at monthly, seasonal, and annual scales.

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The database covers a wide range of climatic zones and ecosystem types across both natural and anthropogenic biomes.

In terms of climatic classification, most records are located in temperate zones, accounting for 60.3% (n = 1446, hereafter "n =" was omitted) of the dataset, followed by boreal zone 18.5% (443), tropical zone 15.7% (377), and alpine zones 5.5% (131). Considering land area, temperate regions account for ~31% of the global land surface but contribute about 60% of the total records, reflecting a sampling bias toward mid-latitude regions. Interestingly, although alpine regions occupy only ~3% of the global land area, they contribute 5.5% of the records in the database, likely due to the inclusion of a relatively large number of SMU studies from the Qinghai–Tibet Plateau in China, which were underrepresented in previous global databases. These findings further highlight the need to enhance future investigations into SMU in tropical regions, which remain underrepresented in current datasets.

The data span a broad range of terrestrial ecosystems, with varying levels of representation. Forests dominate the dataset, contributing 48.1% (n = 1153, hereafter "n =" was omitted) of records, while rainforests, as a specific forest subtype, represent 1.4% (33). Agricultural lands account for 22.4% (538), reflecting the increasing research focus in recent years on the impacts of land use and management on SMU. Grasslands account for 16.7% (399). Although spatially clustered in certain regions, these records collectively cover a wide range of terrestrial ecosystems and climatic zones.

According to the Whittaker biome classification, the global SMU records were categorized into distinct biome types (Fig. 3). The most represented biomes include temperate seasonal forests, which account for 27.6% (n = 662, hereafter "n =" was omitted) of the total dataset, followed by agricultural lands (22.4%, 538), temperate grasslands (11.2%, 269), and boreal forests (10.4%, 248). Less represented biomes include tropical seasonal forests (9.3%, 223), alpine regions (5.5%, 131), and tundra (3.7%, 89).

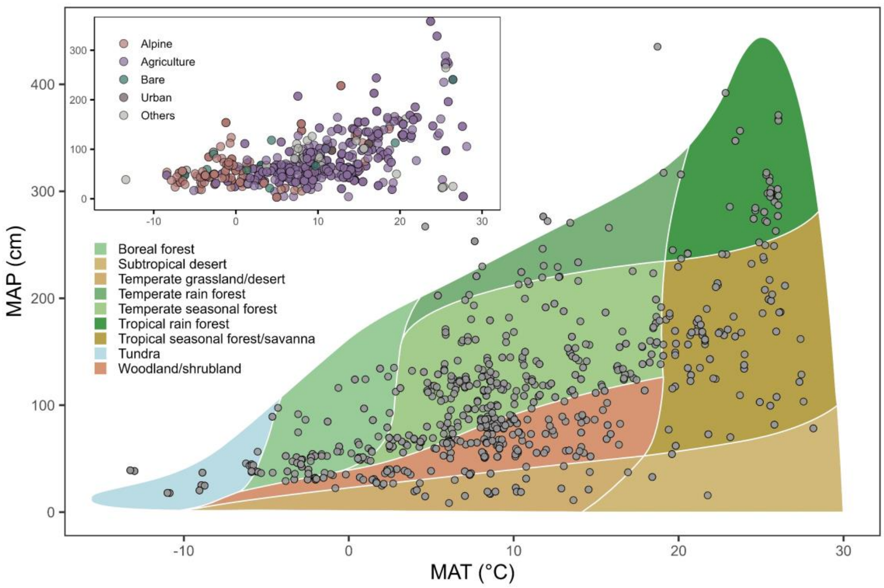

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Figure 3. Distribution of global SMU records (gray markers) within the Whittaker biome framework, which represents global climate space based on mean annual temperature (MAT) and mean annual precipitation (MAP). The inset figure shows the distribution of additional biomes (Alpine, Agriculture, Bare, Urban, and Others) that fall outside the Whittaker classification.

3.3 Observed annual and seasonal fluxes

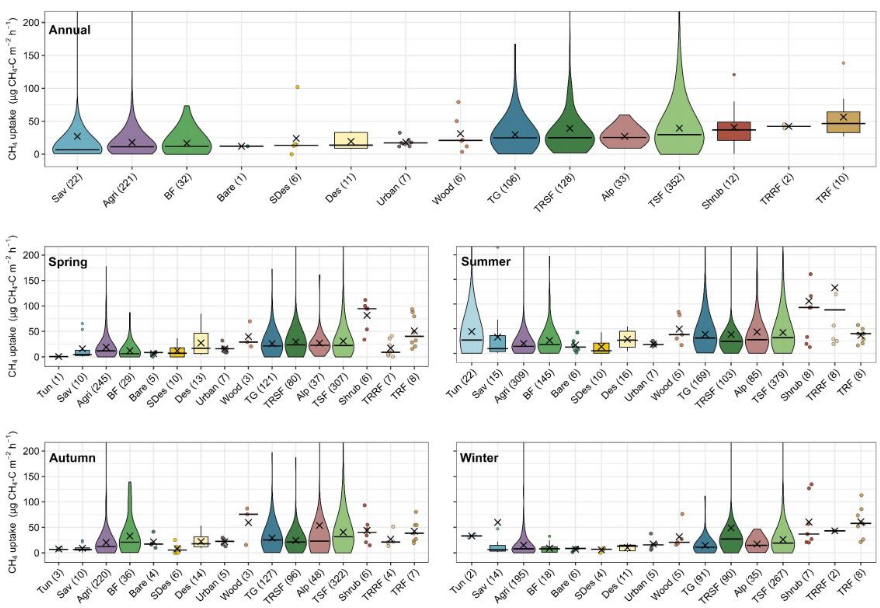

Figure 4. Comparison of annual and seasonal SMU observations across biomes: Tundra (Tun), Boreal Forest (BF), Temperate Seasonal Forest (TSF), Temperate Rainforest (TRF), Tropical Rainforest (TRRF), Tropical Seasonal Forest (TRSF), Savanna (Sav), Subtropical Desert (SDes), Temperate Grassland (TG), Desert (Des), Woodland (Wood), Shrubland (Shrub), Alpine (Alp), Agriculture (Agri), Bare (Bare), and Urban. In the annual panel, biomes are ordered by the median SMU values. Black lines indicate the median CH_4 uptake and the crosses (×) denote the mean for each biome. In violin plots, the width represents the kernel density of observations at a given value. The number of flux values is indicated after each x-axis label. Plot types were selected based on sample size: scatter plots for <10, box plots for 10-20, and violin plots for ⩾20.

On an annual scale (Fig. 4), as commonly recognized in previous studies, forests exhibit the highest CH_4 sink rates compared to grasslands and cultivated soils in the database (Dutaur and Verchot, 2007; Reay et al., 2018; Tate, 2015). Among forest biomes, the notably high median flux observed in rainforests (46.5 µg CH_4–C m^{-2} h^{-1}), differs from some earlier estimates (Dutaur and Verchot, 2007), likely because many previous studies on tropical rainforests

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focused on the hot and wet season (i.e., April-October), which could have led to an underestimation of annual averages. Moreover, many earlier studies grouped rainforests together with other forest types, potentially masking their relatively high SMU (Li et al., 2025). The high fluxes observed in shrublands (Fig. S2) are consistent with results from the Terrestrial Ecosystem Model (TEM) (Zhuang et al., 2013). Alpine regions exhibited the highest SMU across climatic zones (Fig. S3); however, the mean SMU was slightly lower than that reported for alpine grasslands (mean 54.2 μg CH_4–C m^{-2} h^{-1}), likely because the Alpine category aggregates multiple ecosystem types (e.g., forests and grasslands) (Wang et al., 2025). Savanna, agricultural, and desert soils exhibit relatively low CH_4 sink rates, especially in subtropical deserts, likely due to moisture limitation, management practices, nitrogen inputs, barren environmental conditions, and suppressive effects of biological soil crusts (Hu et al., 2022; Jia et al., 2018).

The observed global annual CH_4 uptake rates ranged from ~0.0 to 409.0 (μg CH_4-C m^{-2} h^{-1}, hereafter the same units) with a median of 21.2 (interquartile range: 9.3–39.2). The large variability in SMU and its divergent responses to moisture reflect discrepancies in local environments such as climate (Dutaur and Verchot, 2007), ecosystem type (Wang et al., 2014), and soil properties (Kou et al., 2017). The highest consumption rate was measured in a tropical forest in Hainan, China, whereas the lowest detectable flux was observed in a subtropical desert of Ningxia Hui Autonomous Region, China.

Natural biomes account for the majority of global CH_4 uptake (Zhuang et al., 2004), with particularly high fluxes observed in temperate and tropical regions. In the database, natural biomes such as woodlands (median 21.0 μg CH_4-C m^{-2} h^{-1}, hereafter the same units), temperate grasslands (24.8), tropical seasonal forests (25.0), alpine regions (25.3), temperate seasonal forests (29.8), shrublands (36.9), temperate rainforests (42.3) and tropical rainforests (46.5) all exhibit relatively high CH_4 uptake rates. These results are consistent with previous estimates for temperate and tropical regions (Murguia-Flores et al., 2018; Zhou et al., 2024). In contrast, boreal ecosystems such as boreal forests (11.9), arid regions including savannas (6.7), subtropical deserts (13.5), and deserts (13.7), as well as areas heavily impacted by human activity, such as agricultural lands (11.3) and bare lands (12.1), generally exhibit lower annual CH_4 fluxes. Notably, rainforests show exceptionally high annual CH_4 uptake rates, exceeding 40 μg CH_4-C m^{-2} h^{-1}.

SMU exhibits high seasonal variability across biomes (Figs. 4 and S4). Thirteen biomes show pronounced seasonal variability with $CV \geqslant 20\%$, including tundra (92.3%), temperate rainforests (86.3%), woodlands (59.3%), boreal forests (55.2%), shrublands (48.2%), temperate grasslands (38.0%), bare lands (34.6%), deserts (30.6%), savanna (28.9%), temperate seasonal forests (24.8%), alpine (24.2%), agricultural lands (22.4%), and tropical rainforests (20.9%), mainly due to the intra-annual environmental changes and measurement factors. This emphasizes the critical role of seasonal variability in accurately quantifying CH_4 fluxes across biomes. In addition, for certain ecosystems, comparisons between seasonal fluxes and annual mean data reveal systematic differences, indicating that the estimates without accounting for intra-annual variations could overestimate or underestimate the annual SMU budgets.

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3.4 Monthly variations of each biome

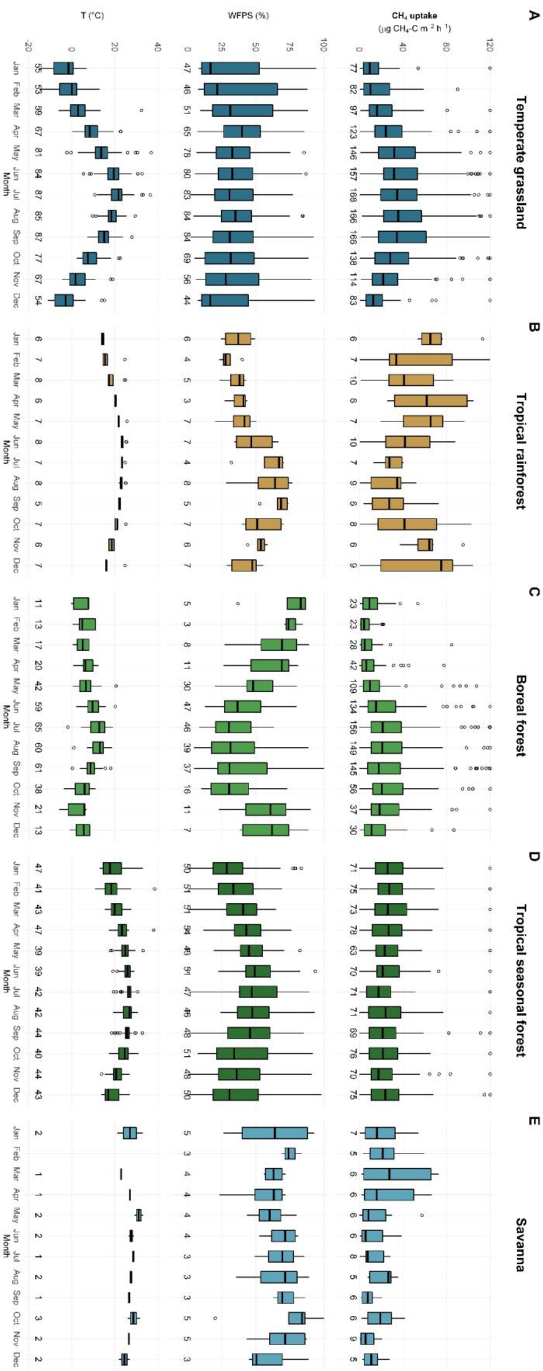

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Figure 5. Intra-annual variations of SMU, soil moisture (expressed as WFPS, water-filled pore space), and soil temperature (T) across biomes in the Northern Hemisphere. The black lines indicate the median CH_4 uptake for each biome. The count of flux values in each month is labeled beneath the x-axis ticks. The biomes were grouped into five categories: (A) temperature-dominated, (B) moisture-dominated, (C) moisture and temperature jointly promoted, (D) moisture and temperature jointly constrained, and (E) no obvious pattern, based on the interactions between moisture and temperature.

At the global scale, monthly SMU anomalies show weak temporal covariation with soil moisture and soil temperature when pooled across all sites (Fig. S5). In contrast, ecosystem-specific mean monthly SMU patterns exhibit strong covariation with soil moisture and soil temperature (Figs. 5 and S5). The large variability in SMU and its divergent sensitivities to moisture and temperature reflect heterogeneity in local environmental conditions. In general, low soil moisture inhibits CH_4 oxidation by depressing microbial metabolism (Yue et al., 2022), and high soil moisture restrains CH_4 uptake by reducing CH_4 diffusion (Shukla et al., 2013). Across ecosystems, SMU exhibits either positive or negative sensitivity to soil moisture, depending on ecosystem type and background moisture conditions. Soil temperature largely follows air-temperature seasonality, with peaks in warm seasons and minima in cold seasons. The combined effects of soil temperature and moisture result in distinct patterns and magnitudes of SMU across ecosystems.

Based on the interactive effects of soil moisture and soil temperature on SMU dynamics, biomes were classified into five groups (Fig. 5): temperature-dominated (e.g., Temperate Grassland; Fig. 5A) and moisture-dominated (e.g., Tropical Rainforest; Fig. 5B), where the monthly variability of SMU aligns more closely with changes in soil temperature or soil moisture, respectively; jointly promoted (e.g., Boreal Forest; Fig. 5C), characterized by clear seasonal cycles in both drivers and a corresponding seasonal pattern in SMU; jointly constrained (e.g., Tropical Seasonal Forest; Fig. 5D), which shows pronounced seasonality in temperature and moisture but weak, noisy, or indistinct intra-annual variation in SMU; and no obvious pattern (e.g., Savanna; Fig. 5E), referring to cases where neither soil temperature, soil moisture, nor SMU exhibits a clear seasonal cycle, or where their seasonal variations do not correspond, potentially due to limited observations. Among these, Deserts (Fig. S6L) are located on the drier-than-optimal side of the soil moisture optimum, so increasing moisture enhances CH_4 uptake; we therefore classify deserts as moisture-dominated. In the Southern Hemisphere, soil temperature seasonality is opposite to that in the Northern Hemisphere, and no consistent SMU seasonality is evident across most biomes, likely reflecting sparse data coverage and limited land area (Fig. S7).

Monthly SMU exhibits pronounced heterogeneity across both temporal and spatial scales within and among sites, ranging from ~0 to 792.9 μg CH_4-C m^{-2} h^{-1} (see Supplementary file "Studies and Fluxes"). The variability of monthly mean soil CH_4 fluxes in each ecosystem was quantified using the *CV* (see Methods, Fig. S8). In the Northern Hemisphere, *CV*s for 16 biomes exceed 10%, indicating moderate to high intra-annual variability and pronounced differences in seasonal SMU amplitude among biomes. The largest median monthly SMU occurred in August in shrublands, whereas the smallest occurred in November in subtropical deserts.

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4 Future development and access to SMUD

4.1 Weaknesses of the current SMUD

The current literature search was insufficient to capture all studies related to SMU, particularly those conducted in environments with intermittent CH_4 uptake, such as riparian zones, wetlands, and seasonally wet agricultural regions. Measurements reported in publications written in languages other than English or Chinese are not included in the database. Furthermore, the existing data structure could be streamlined and automated to facilitate easier access and analysis.

As new SMU studies continue to be published rapidly, additional data are continually emerging. We intend to maintain and periodically update a dynamic version of this database. Over time, we envision these updates evolving into a collaborative effort involving the broader user community, ultimately transforming the database into a shared resource that can be integrated with other related initiatives.

4.2 Future development and applications

SMUD has broad applications across multiple disciplines, including biogeochemistry, ecology, and climates. A global SMU database provides harmonized measurements of CH_4 fluxes and environmental drivers and incorporates standardized soil parameters (e.g., soil moisture and soil temperature), thereby supporting more accurate bottom-up estimates of the soil CH_4 sink. This database also enables process-based models to represent SMU more mechanistically, reducing uncertainty in global SMU estimates, helping reconcile discrepancies with top-down atmospheric inversions, and improving predictions of CH_4–climate feedbacks under global change (Luo et al., 2013; Murguia-Flores et al., 2018; Ni and Groffman, 2018; Saunois et al., 2025; Smith et al., 2000). By unifying flux measurements across biomes (e.g., tundra, boreal forests, savanna, and agricultural areas), the database enables to reveal the spatiotemporal patterns of SMU and to examine the response of SMU to climate, vegetation, and land use (Dutaur and Verchot, 2007). Integrating point-based SMU data with Earth observation products enables upscaling of CH_4 uptake estimates from local sites to regional and global scales (Oertel et al., 2016; Tian et al., 2016). The database further offers essential ground truth for calibrating and validating satellite-based and process-based estimates of global SMU.

In Earth system science, shared databases supported by modern computational tools can expand the user community, strengthen analytical capacity, and enhance public trust. Moreover, version-control technologies from the open-source community enable "living" databases that can be continually updated and improved by their users (Bond-Lamberty and Thomson, 2010). Thus, our goal is to build a global database of published SMU data and provide it to researchers both as a traditional static archive and as a dynamic, community-driven resource.

4.3 Database access and updates

All data and code used to reproduce the results in this study are available at

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https://doi.org/10.5281/zenodo.18299391 (Jiang et al., 2026). The data are licensed under the Creative Commons Attribution 4.0 International license (CC BY 4.0, https://creativecommons.org/licenses/by/4.0/), and the accompanying code is licensed under the open-source MIT license (https://opensource.org/license/mit)..

5 Conclusions

SMUD provides a comprehensive global dataset of SMU across both temporal and spatial dimensions. The database includes data at four temporal scales—daily, monthly, seasonal, and annual—and spans a wide range of climatic zones and ecosystem types. Seasonal variation is shown to be essential for understanding intra-annual changes in SMU and elucidating its spatiotemporal patterns. The data reveal distinct SMU capacities across biomes. The overlooks of biome diversity within ecosystem types contribute to the uncertainty in SMU estimates due to failing to reliably capture the intra-ecosystem differences of SMU.

SMUD is intended to compile and make accessible the broad body of SMU studies, mainly published over the past three decades. In addition, the database aspires to harness open-source software technologies to foster a dynamic, collaborative, and continually improving data platform for researchers and other users in the biological, environmental, and Earth sciences.

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Author contributions

Z.Y. and J.W.J. conceived this study; Z.Y., J.S.J and J.W.J. designed the primary analysis; J.W.J. built the database, developed the model code and wrote the first draft. All authors contributed to data interpretation and preparation of manuscript text.

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