A Global Database of Soil Methane uptake (SMUD)

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Abstract

Soil methane uptake (SMU), the important biological sink for atmospheric methane (CH_4) in terrestrial ecosystems, represents an important component of the global CH_4 budget. Although field SMU observations have been conducted since the 1980s, they have not yet been systematically compiled into a unified and openly available database. Here, we present the global Soil Methane Uptake Database (SMUD), which includes 2,427 site-level records from 920 peer-reviewed publications spanning 1986 to 2025. SMUD contains SMU measurements at multiple temporal scales, including daily (n = 1,425), monthly (n = 2,001), seasonal (n = 1,720), and annual (n = 1,098), together with associated soil moisture and soil temperature data at daily and monthly scales where available. The collected datasets cover all major climatic zones and ecosystem types and reveal pronounced spatial and temporal variability in SMU.. Our analyses show that seasonal- and biome-specific patterns are important for understanding intra-annual variability in SMU. In particular, quantitative classification showed that the relationships of SMU with soil temperature and moisture differed among biomes, making ecosystems to be grouped into four response types: temperature-dominated, moisture-dominated, jointly regulated by temperature and moisture, and no clear dominant control. Overall, SMUD provides a comprehensive basis for characterizing global SMU patterns,

investigating underlying mechanisms, and improving estimates of the global SMU budget. The database, associated data, and code for reproducing the results are available at https://doi.org/10.5281/zenodo.18299391 (Jiang et al., 2026). We aim to maintain SMUD as a collaborative, community-supported, and regularly updated resource for the research community.

1 Introduction

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

Among the major long-lived greenhouse gases, methane (CH_4) has contributed approximately 0.5 °C to global warming and accounts for about 30% of observed global warming (Masson-Delmotte et al., 2021; Shindell et al., 2012). Per unit mass, CH_4 exerts a stronger warming effect 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 has reflected a sustained imbalance between its emissions and sinks (Gauci et al., 2024). CH_4 mitigation has thus become a central focus of international climate policy, as highlighted by the Global Methane Pledge, which aims to reduce anthropogenic CH_4 emissions by at least 30% by 2030 relative to 2020 levels (Saunois et al., 2025). In this context, a comprehensive understanding of both anthropogenic sources and natural sinks is essential to accurately assess the net CH_4 budget and mitigation potential.

Soils are key environments for CH_4 cycling, where CH_4 is consumed by aerobic methanotrophs and generated by anaerobic methanogens. The resulting net CH_4 flux is therefore determined by the balance between CH_4 oxidation and production, which is regulated by multiple environmental and biological factors influencing methanotrophic and methanogenic activities (Ni and Groffman, 2018; Bridgham et al., 2013). Soil methane uptake (SMU), driven by the microbial oxidation of atmospheric CH_4, represents the second-largest atmospheric CH_4 sink after atmospheric oxidation and the major biologically mediated oxidative sink in terrestrial ecosystems (Song et al., 2024; Saunois et al., 2025). However, human land-use change has substantially weakened 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 have been up to three times higher, reaching 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 has been growing at approximately 19.0–36.0 Tg CH_4 yr^{-1} during this century, strengthening SMU could provide a complementary opportunity to partially offset 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 through changes in land use, soil properties, and management practices (De Bernardi et al., 2022).

Global SMU estimates remain highly uncertain, with bottom-up estimates ranging from 11 to 49 Tg CH_4 yr^{-1} (Saunois et al., 2025). This uncertainty arises in part from the substantial spatiotemporal variability of SMU (Jiang et al., 2025). Temporally, continuous measurements have revealed large fluctuations, with interannual variability reaching up to 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 variations are shaped by environmental conditions and management practices, both of which introduce substantial uncertainty into global SMU estimation (Song et al., 2024). Current global SMU estimates generally rely on data-driven or process-based approaches. Data-driven methods aggregate observations across ecosystems or climate zones but are limited by observational bias, limited spatial coverage and coarse spatial representation. Process-based models simulate grid-scale SMU by representing CH_4 oxidation and diffusion processes, but they commonly rely on spatially invariant or weakly constrained parameters, which may be inconsistent with observations and lead to divergent estimates (Jiang et al., 2025). Together, these limitations indicate that a major source of uncertainty in current global SMU estimates arises from model parameterization and the limited observational basis used to constrain model parameters. Addressing this issue requires a more comprehensive, standardized, and robust global database to better support model development, parameter optimization, and large-scale SMU assessment.

1.2 The need for a unified global SMU database

Many field measurements have been conducted since the 1980s to measure SMU across a wide range of climatic conditions and ecosystems (see Supplementary file "CH_4 uptake data_CH_4 FLUX_1_1410", Fig. 1). However, most existing SMU estimates rely on small-scale and site-specific observations, which remain difficult to synthesize because of fragmented reporting, inconsistent measurement units, and the lack of standardized approaches across research groups. Therefore, standardizing and integrating existing SMU measurements into a coherent data framework is essential for supporting synthesis studies and advancing global CH_4 cycle research.

Since 2000, several databases based on in situ measurements have been developed to support global SMU estimates (Jiang et al., 2025). However, these databases have limited representation across ecosystems and climatic zones and are therefore insufficient to fully capture the spatiotemporal variability of SMU. For example, Grosso et al. (2000) focused on observations from Europe and North America rather than providing a global assessment. Dutaur et al. (2007) presented a global estimate, but their dataset was still dominated by observations from Europe and North America. Although Murguia-Flores et al. (2018) reported global SMU estimates, their analysis was based on a relatively limited database comprising approximately 100 observations from about 30 studies.

Although the number of SMU measurements has increased over time, existing databases remain inadequate for robustly estimating global SMU. Most global SMU estimates have been derived from data with low temporal resolution, often relying on annual averages that overlook important 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, compiling comprehensive and standardized global SMU measurements, together with associated soil physicochemical properties where available, is essential for generalizing and upscaling existing observations and improving the reliability of SMU estimates. Such a database would also facilitate research linking SMU to key soil biogeochemical processes (Aronson and Helliker, 2010) and plant-associated processes (Voigt et al., 2023; Chai et al., 2020) that regulate SMU, as well as modeling SMU responses to changing environmental conditions (Song et al., 2024; Murguia-Flores et al., 2018).

Our primary aim is to harmonize disparate data sources, standardize measurement units, compile associated metadata, and integrate global SMU observations into a comprehensive database across multiple temporal and spatial scales. We also aim to provide an open and robust platform that facilitates synthesis, benchmarking, and modeling of SMU dynamics under varying climatic and environmental conditions. Furthermore, we aim to foster collaboration and knowledge exchange within the scientific community, thereby supporting evidence-based assessments relevant to CH_4 mitigation planning and climate change research.

2 Methods

2.1 Database compilation

Relevant peer-reviewed publications reporting SMU were identified through a systematic search of two literature 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 screened to determine eligibility. In total, approximately 10,800 papers were retrieved.

Studies were considered eligible if they met the following criteria: (i) they reported in situ field measurements of SMU; laboratory incubation experiments and purely modeling-based studies without field observations were excluded; (ii) when multiple experimental treatments were reported, the unamended control treatment was selected; (iii) they reported at least one type of temporally aggregated SMU data, including daily, weekly, monthly, seasonal, or annual values. Measurements made at hourly resolution within a single day were excluded. The flux data in SMUD were organized into four categories based on temporal aggregation: Daily (see Supplementary file "CH_4 uptake data_CH_4 FLUX_1_1410"), 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). In this study, "site-level records" refer to unique database entries compiled from individual studies and sites, whereas "measurements" refer to CH_4 flux values available at specific temporal resolutions. A single site-level record may contribute measurements at daily, monthly, seasonal, and annual resolutions. 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, region, climatic characteristics, and ecosystem type (e.g., forest, grassland, and agriculture) was also collected (Table 1; Supplementary file "Studies and Fluxes"). Mean annual temperature (MAT) and mean annual precipitation (MAP) for each site were extracted from ERA5-Land Monthly Aggregated data (Fig. S1; doi:10.24381/cds.68d2bb30). When latitude, longitude, or elevation was missing, the missing information was supplemented using Google Earth (https://earth.google.com/) based on the original site description.

The data were categorized according to the Whittaker biome classification (Fig. 2), including tundra (Tun), boreal forest (BF), temperate seasonal forest (TSF), temperate rainforest (TRF), temperate grassland (TG), desert (Des), tropical rainforest (TRRF), tropical seasonal forest (TRSF), savanna (Sav), subtropical desert (SDes), woodland (Wood), and shrubland (Shrub). Observations outside the Whittaker biome framework were reclassified into additional categories, including alpine (Alp), agricultural land (Agri), bare land (Bare), urban areas (Urban), and others. The "others" category included special habitats or sources not represented in the Whittaker framework, such as saline-alkaline soils, blanket peats, landfills, wetlands, riparian zones, floodplains, ant nests, and atmosphere–soil–cave systems.

2.2 Database structure

The "Studies and Fluxes" file contains publication information, site-specific metadata, including location, climatic characteristics, and ecosystem type, and experimental details, including sampling time, measurement duration, sampling frequency, and measurement methods; field descriptions are provided in Table 1. This file also includes monthly, seasonal, and annual SMU fluxes, either as reported by the original authors or derived from shorter-timescale measurements. The second file, named "CH_4 uptake data_CH_4 FLUX_1_1410", contains the compiled daily and monthly SMU measurements (Table 2). Each record includes information on the sampling year, day of year (DOY), and corresponding SMU fluxes. A unique identifier (Paper–Study ID) links corresponding entries between the two files..

In the "CH_4 uptake data_CH_4 FLUX_1_1410" the original SMU units reported in the source publications were retained and described using four components: gas species, mass basis, area basis, and time basis. For cross-study comparison, all SMU values were converted to a standardized unit of μg CH_4-C m^{-2} h^{-1}. When CH_4 fluxes were expressed as CO_2-equivalents, a 100-year global warming potential factor of 27.2 was used for CH_4 relative to CO_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 "CH_4 uptake data_CH_4 FLUX_1_1410" file contains 6 fields (Table 2).

Table 1. Categories of database fields and corresponding descriptions for the Supplementary file "Studies and Fluxes". SMU values in this file have been standardized to unified units of μg CH_4–C m^{-2} h^{-1} for comparison across studies.

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	℃	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

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

Table 2. Categories of database fields and corresponding descriptions for the Supplementary file "CH_4 uptake data_CH_4 FLUX_1_1410". Original flux values and units are preserved as reported in the corresponding literature records and have not been standardized in this table.

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 quality-control (QC) procedure was applied to the database, and quality flags (Q01–Q07) were used to identify records with known issues, potential uncertainties, or specific data characteristics. When multiple sources of the same SMU value were available, values directly reported by the authors were prioritized over values calculated from other reported data or digitized from figures. Laboratory incubation data (Q01) and duplicate records (Q02) were excluded from subsequent analyses. The specific sampling time was recorded to improve 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 as Q03 and assigned to the "Other" category for sampling time in the "Studies and Fluxes" file. Because incorrect units may result in unrealistic flux values, confirmed and suspected unit errors were identified based on unit-conversion checks and information from figures, tables, and relevant textual descriptions; these records were flagged as Q04. Records with confirmed erroneous flux units in the original publications were excluded from the analysis. Site coordinates and locations were checked using Google Earth (https://earth.google.com/) to identify and correct inaccurately reported site locations; corrected records were flagged as Q05. For records lacking coordinate information, geographic coordinates were supplemented based on the descriptions of study sites or plots. Records with unresolved uncertainties or other known data issues that could not be assigned to Q01–Q05 were flagged as Q06 to alert users to potential problems. In addition, daily-scale records were identified using Q07; this flag indicates temporal resolution rather than a data-quality problem.

2.4 Data analysis

The consistency between MAT and MAP reported in the original studies and those derived from ERA5-Land was assessed by extracting ERA5-Land values from the 0.1° grid cells corresponding to site coordinates and fitting linear regressions between ERA5-Land-derived and study-reported values. Regression slope, intercept, R^2, and N were reported, with the 1:1 line shown as a reference (Fig. S1). ERA5-Land–derived MAT and MAP showed strong agreement with study-reported values (MAT: $R^2 = 0.86$, slope = 0.898; MAP: $R^2 = 0.79$, slope = 0.781). Locally measured or site-reported MAT and MAP values were prioritized when available, particularly for sites located in mountainous areas with strong elevation gradients. SMU values were obtained either directly from the literature or derived from shorter-timescale measurements. Monthly SMU fluxes from January to December were calculated as arithmetic means of daily fluxes within the corresponding DOY ranges for each site or study record. 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 when the original study reported paired seasonal values representing the full annual cycle, such as growing versus dormant seasons or wet versus dry seasons. 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 using the same DOY ranges. 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):

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

where *BD* is bulk density (g cm^{-3}); when *BD* was not reported, it was retrieved from SoilGrids250m 2.0 (Poggio et al., 2021), and 2.65 g cm^{-3} is the assumed particle density. All data were initially organized in Microsoft Excel and archived as CSV files in the supplementary files "Studies and Fluxes" and "CH_4 uptake data_CH_4 FLUX_1_1410". The *coefficient of variation (CV)* was used to quantify the relative magnitude of intra-annual SMU variability:

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

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

where σ is the standard deviation, x_i is the i-th observation, μ is the 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).

To support the classification of temperature-dominated, moisture-dominated, jointly controlled, and no-clear-dominance systems, we conducted ecosystem-specific regression analyses of SMU as a function of soil temperature and soil moisture using standardized variables (Schielzeth, 2010). For each ecosystem group, we fitted multiple linear regression models with standardized variables, using SMU as the response variable and soil temperature and soil moisture as predictors. The relative importance of temperature and moisture was evaluated based on the significance and absolute magnitude of the standardized regression coefficients. Ecosystems were classified as temperature-dominated when the temperature coefficient was significant and larger than the moisture coefficient, moisture-dominated when the moisture coefficient was significant and larger than the temperature coefficient, jointly controlled when both predictors were significant and showed comparable standardized effects. Ecosystems that did not meet these criteria were classified as having no clear dominant control. These analyses were intended to support descriptive classification of empirical patterns rather than establish causal mechanisms.

Data processing and calculations were performed using MATLAB R2021a (MATLAB code files 1–3). Figures were generated using R version 4.5.0 (R Core Team, 2025; R code files 1–11). The major R packages used for plotting included ggplot2, dplyr, tidyr, readxl, and patchwork.

3 Results and discussion

3.1 Overview of the SMUD

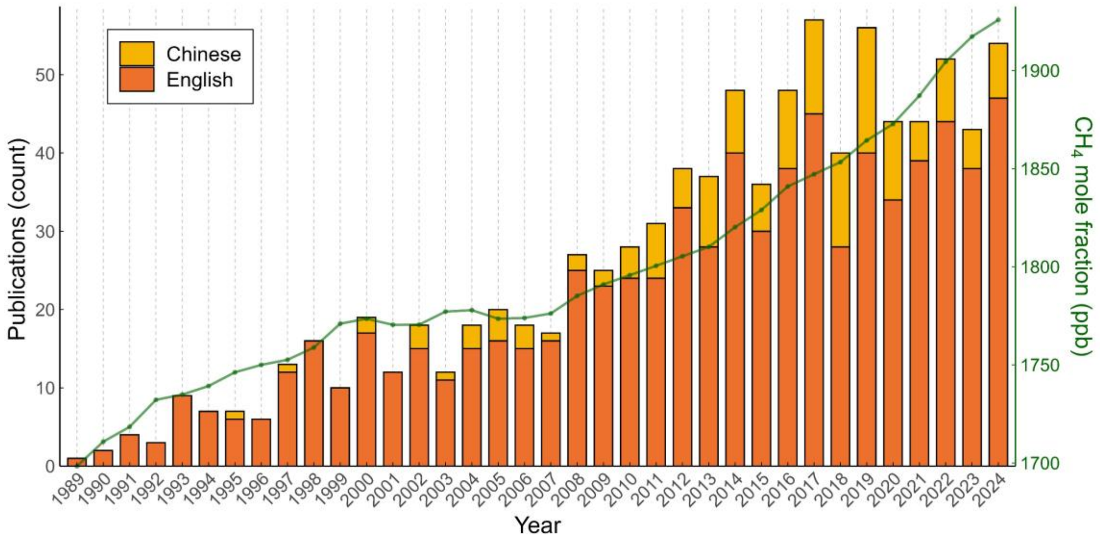

Figure 1. Temporal trends in peer-reviewed publications on soil methane uptake (SMU), from the Web of Science and CNKI databases. The green line indicates the globally averaged atmospheric CH_4 concentration (adapted from NOAA Global Monitoring Laboratory records).

Before the final data screening and filtering procedures, all 3,050 initially compiled records were evaluated using the Q01–Q07 QC system to identify potential issues and improve data transparency. The proportions of records flagged as Q01–Q07 were 0.56% (n = 17), 0.03% (n = 1), 17.44% (n = 532), 2.69% (n = 82), 4.13% (n = 126), 0.23% (n = 7), and 47.70% (n = 1,455), respectively. These QC flags were primarily used to annotate potential data limitations or specific data characteristics prior to subsequent filtering and harmonization procedures. Because individual records may contain multiple QC flags, the reported percentages are not mutually exclusive. The current database includes 2,427 site-level records from 1,155 sites extracted from 920 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 1,425 daily-scale measurements from 681 sites, 2,001 monthly-scale measurements from 973 sites, 1,720 seasonal-scale measurements from 795 sites, and 1,098 annual-scale measurements from 535 sites.

The number of SMU studies has gradually increased since the 1980s, with a marked increase over the past two decades. The expansion of SMU studies may be partly associated with advances in CH_4 measurement techniques. Measurement approaches have evolved from laboratory wet-chemical analyses to gas chromatography, automated chamber systems, laser spectroscopy, and broader atmospheric CH_4 monitoring, enabling observations across multiple temporal and spatial scales (Khalil et al., 1989; Werle et al., 1993; Baldocchi, 2003; Crosson, 2008; Jacob et al., 2016). The increase in SMU publications also appears to coincide with shifts in atmospheric CH_4 over the last 40 years; after a relatively stable period, atmospheric CH_4 concentrations began to rise again around 2007 (Reay et al., 2018). One possible interpretation is that the renewed increase in atmospheric CH_4 may have contributed to increased scientific attention to SMU.

3.2 Spatial distribution of data

The database provides 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 (1,023), 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 remain sparsely represented (Fig. 2). This uneven geographical distribution reflects the current availability of field observations but may introduce additional uncertainty in global extrapolation and large-scale modeling applications, especially in regions with sparse observational coverage.

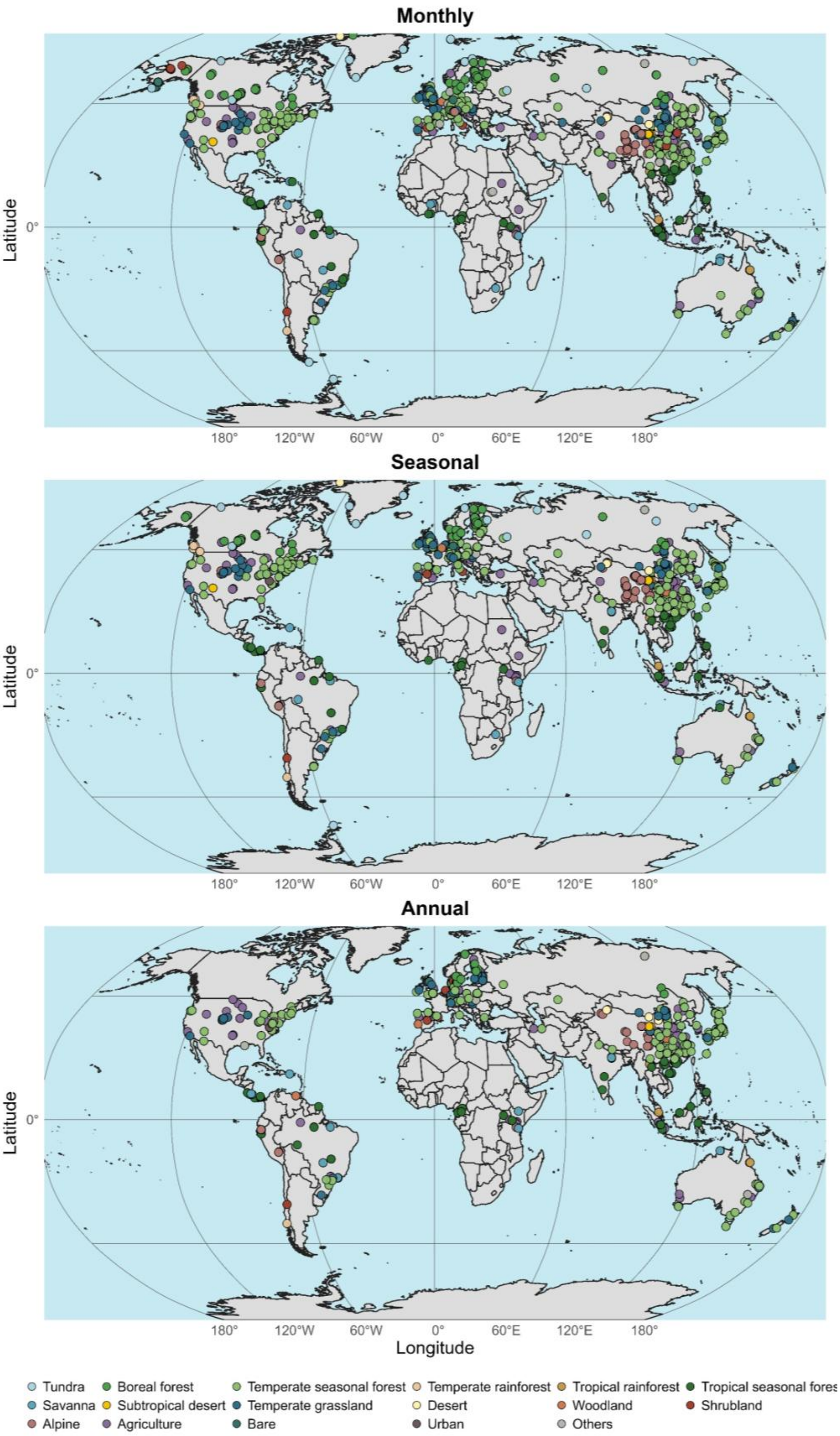

Figure 2. Geographic distribution of global SMU measurement sites across biomes at monthly, seasonal, and annual scales.

The database covers a wide range of climatic zones and ecosystem types across both natural and human-modified ecosystems.

In terms of climatic classification, most records are located in temperate zones, accounting for 60.3% (n = 1,446, hereafter "n =" was omitted) of the dataset, followed by boreal zone 18.5% (443), tropical zone 15.7% (377), and alpine zone 5.5% (131). Relative to their global land area, temperate regions are overrepresented: they account for approximately 31% of the global land surface but contribute about 60% of the total records, reflecting a sampling bias toward mid-latitude regions. By contrast, although alpine regions occupy only approximately 3% of the global land area, they contribute 5.5% of the records in SMUD, likely because this database includes a relatively large number of SMU studies from the Qinghai–Tibet Plateau in China, a region that was underrepresented in previous global databases. These findings further highlight the need to increase future SMU observations in tropical regions, which account for approximately 24% of the global land area yet contain only 15.7% of the records. This imbalance may weaken model calibration and evaluation in tropical regions, thereby contributing to uncertainty in global SMU budget estimates.

Ecosystem representation also varied substantially across the database. Forests represent the largest share of the dataset, contributing 48.1% (n = 1,153, hereafter "n =" was omitted) of records. Within the forest category, rainforests account for 1.4% (33). Agricultural lands account for 22.4% (538), possibly reflecting increasing research interest in the effects 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.

Despite spatial clustering in certain regions, these records collectively provide broad ecosystem and climatic coverage (Fig. 3). The best 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).

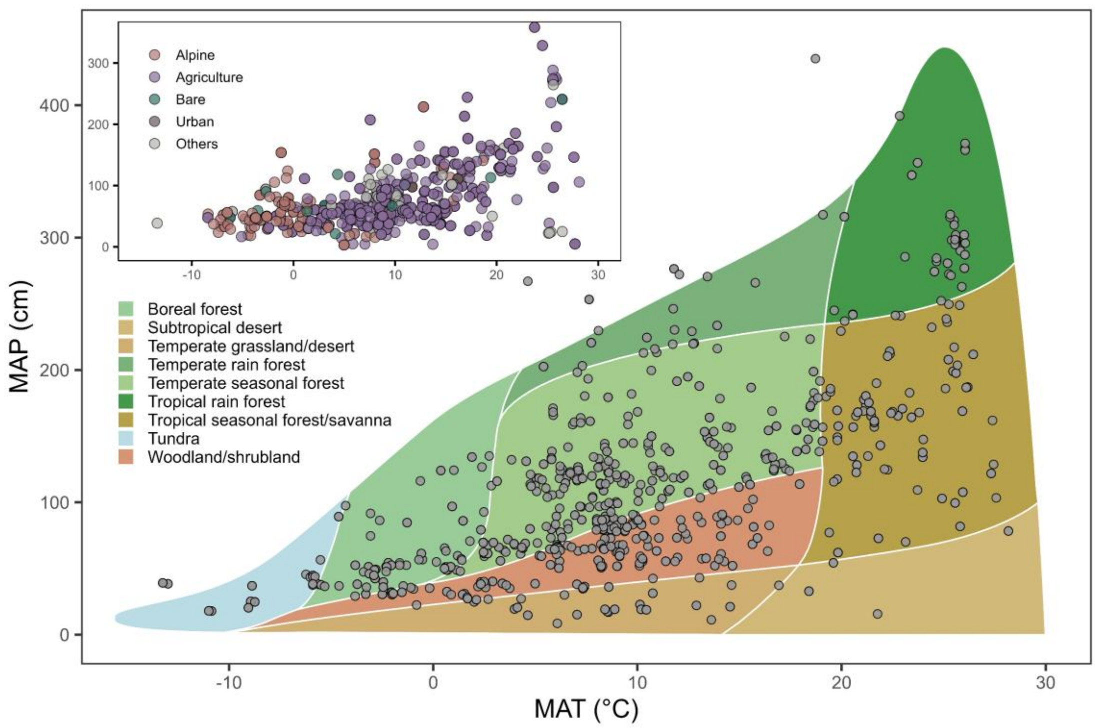

Figure 3. Distribution of global SMU records (gray markers) within the Whittaker biome framework, which represents global climate space based on mean annual temperature (MAT) and mean annual precipitation (MAP). The inset shows the distribution of additional biome categories (Alpine, Agriculture, Bare,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

3.3 Observed annual and seasonal fluxes

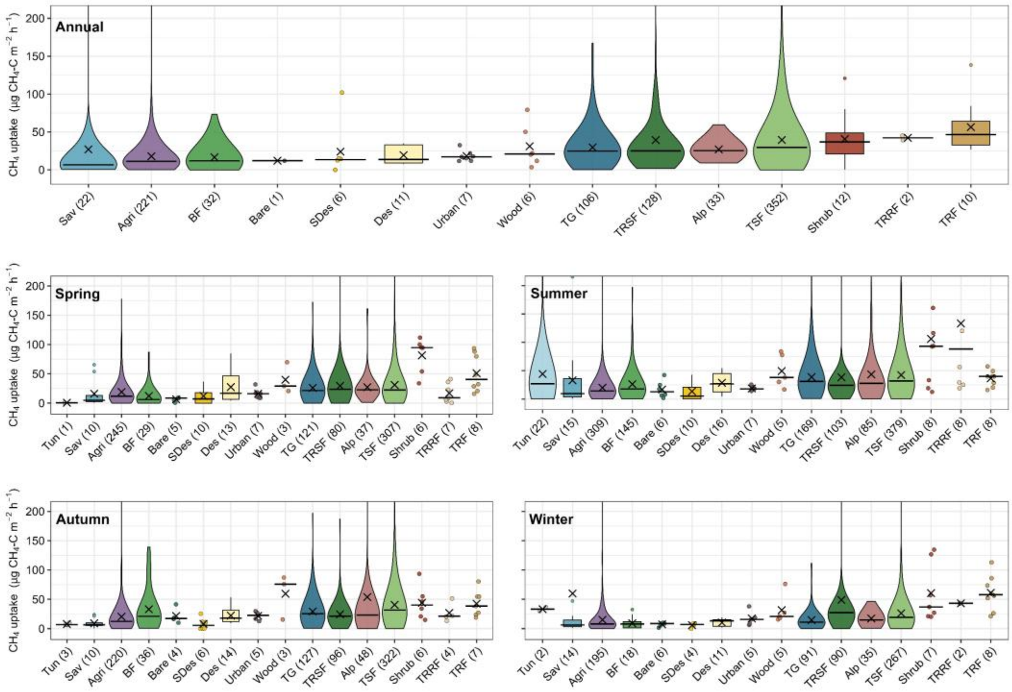

Figure 4. Comparison of annual and seasonal SMU observations across biomes: Tundra (Tun), Boreal Forest (BF), Temperate Seasonal Forest (TSF), Temperate Rainforest (TRF), Tropical Rainforest (TRRF), Tropical Seasonal Forest (TRSF), Savanna (Sav), Subtropical Desert (SDes), Temperate Grassland (TG), Desert (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 SMU 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 $n < 10$, box plots for $10 \leq n < 20$, and violin plots for $n \geq 20$.

At the annual scale, forests generally exhibited higher SMU than grasslands and cultivated soils in the database, consistent with previous studies (Fig. 4; Dutaur and Verchot, 2007; Reay et al., 2018; Tate, 2015). Among forest biomes, the high median fluxes observed in tropical rainforests (46.5 μg CH_4–C m^{-2} h^{-1}) and temperate rainforests (42.3 μg CH_4–C m^{-2} h^{-1}), differ from some earlier estimates (Dutaur and Verchot, 2007). This discrepancy may partly reflect seasonal sampling bias in earlier tropical rainforest studies, many of which focused on the hot and wet season, potentially leading to underestimated 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 SMU observed in shrublands (Fig. S2) are consistent with results from the Terrestrial Ecosystem Model (TEM) (Zhuang et al., 2013). Alpine regions showed the highest SMU among climatic zones (Fig. S3); however, their mean SMU was slightly lower than the value reported for alpine grasslands (mean 54.2 μg CH_4–C m^{-2} h^{-1}), likely because the Alpine category in this study includes multiple ecosystem types, such as forests and grasslands (Wang et al., 2025). Savanna, agricultural, and desert soils exhibited relatively low SMU, especially in subtropical deserts, probably due to moisture limitation, land-management practices, nitrogen inputs, sparse vegetation and harsh environmental conditions, and the suppressive effects of biological soil crusts (Hu et al., 2022; Jia et al., 2018).

The observed global mean annual SMU ranged from approximately 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, together with its divergent responses to soil moisture, likely reflects differences in local environmental conditions, including climate (Dutaur and Verchot, 2007), ecosystem type (Wang et al., 2014), and soil properties (Kou et al., 2017). Within our database, the highest CH_4 consumption rate was recorded in a tropical forest in Hainan, China, whereas the lowest detectable flux was observed in a subtropical desert in Ningxia Hui Autonomous Region, China.

Natural biomes account for the majority of global SMU (Zhuang et al., 2004), with particularly high SMU observed in temperate and tropical regions. In the database, natural biomes showed relatively high SMU, including 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 SMU. These patterns 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), and human-impacted areas, such as agricultural lands (11.3) and bare lands (12.1), generally showed lower annual mean SMU. Notably, rainforests show exceptionally high annual mean SMU, exceeding 40 μg CH_4-C m^{-2} h^{-1}.

SMU exhibits high seasonal variability across biomes (Figs. 4 and S4). Thirteen biomes showed pronounced seasonal variability, $CV \geqslant 20\%$: Thirteen biomes showed pronounced seasonal variability, with CV values ≥20%: 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%), savannas (28.9%), temperate seasonal forests (24.8%), alpine regions (24.2%), agricultural lands (22.4%), and tropical rainforests (20.9%). This variability may reflect intra-annual environmental changes as well as differences in measurement timing and sampling frequency. These findings emphasize the importance of accounting for seasonal variability when quantifying SMU across biomes. In addition, comparisons between seasonal fluxes and annual mean values in certain ecosystems revealed systematic differences, indicating that estimates that do not account for intra-annual variation may overestimate or underestimate annual SMU budgets.

To evaluate the potential influence of excluding CH_4 emission records, we quantified the number and proportion of negative flux values. Negative values accounted for 10.72% of the annual records. Seasonally, the proportion of negative records ranged from 9.79% in autumn to 12.83% in winter and was also relatively high in summer (12.43%). The influence of this filtering varied among biomes. Agricultural soils had the largest absolute number of excluded annual emission records, which accounted for 17.84% of valid annual observations in this biome. These results indicate that CH_4 emissions occurred in a subset of observations. Therefore, excluding these records may influence estimates of mean CH_4 uptake and seasonal variability, particularly during periods when soils temporarily shift from CH_4 sinks to CH_4 sources.

3.4 Monthly variations of each biome

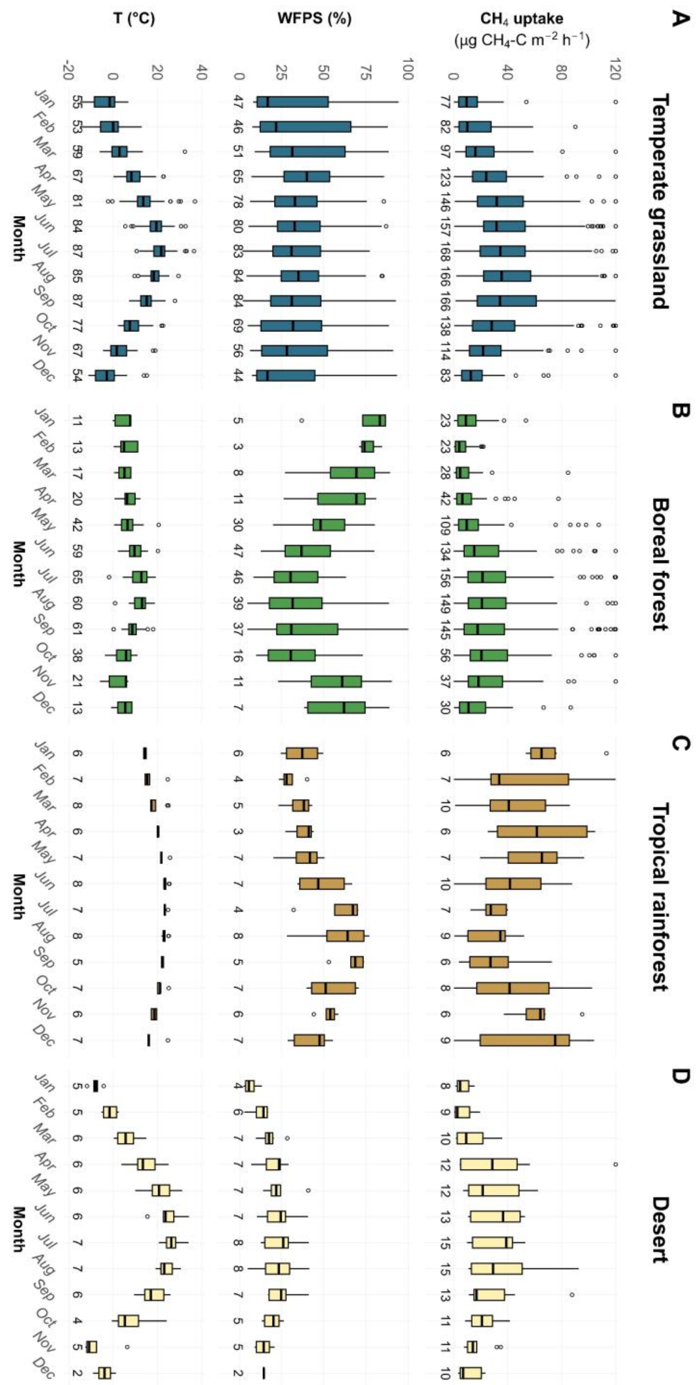

Figure 5. Intra-annual variations of SMU, soil moisture (expressed as WFPS, water-filled pore space), and soil temperature (T) across biomes in the Northern Hemisphere. The black lines indicate the median SMU for each biome. The count of flux values in each month is labeled beneath the x-axis ticks. The biomes were grouped into four categories: (A) temperature-dominated, (B) moisture-dominated, (C) jointly controlled, (D) no clear dominant control, based on the covariation of SMU with soil moisture and soil temperature.

At the global scale, monthly SMU anomalies showed weak temporal covariation with soil moisture and soil temperature when data were pooled across all sites (Fig. S5). In contrast, ecosystem-specific mean monthly SMU patterns showed stronger covariation with soil moisture and soil temperature (Figs. 5 and S5). The large variability in SMU and its divergent sensitivities to soil moisture and temperature likely reflect heterogeneity in local environmental conditions. In general, low soil moisture can inhibit CH_4 oxidation by suppressing microbial metabolism (Yue et al., 2022), whereas high soil moisture can constrain SMU by reducing CH_4 diffusion into soil pores (Shukla et al., 2013). Across ecosystems, SMU showed either positive or negative sensitivity to soil moisture, depending on ecosystem type and background moisture conditions. Soil temperature generally followed air-temperature seasonality, peaking in warm seasons and reaching minima in cold seasons. The combined effects of soil temperature and soil moisture may therefore lead to distinct seasonal patterns and magnitudes of SMU across ecosystems.

Based on the covariation between SMU dynamics and soil hydrothermal variables, biomes were classified into four groups (Fig. 5). In temperature-dominated (e.g., Temperate Grassland; Fig. 5A), where SMU generally increased from winter to summer, broadly following the seasonal increase in soil temperature, whereas the seasonal pattern of soil moisture was less consistently aligned with SMU. In moisture-dominated (e.g., Boreal Forest; Fig. 5B), where seasonal variation in SMU corresponded more closely to changes in soil moisture, suggesting that moisture availability and associated diffusion constraints may be more important controls on SMU. In jointly controlled (e.g., Tropical Rainforest; Fig. 5C), characterized by both soil temperature and soil moisture showing significant associations with SMU, which indicates that seasonal SMU in tropical rainforest cannot be attributed primarily to a single driver; rather, temperature and moisture likely act together to shape observed SMU variability; In contrast, some ecosystems were classified as having no clear dominant control (e.g., Desert; Fig. 5D), because neither soil temperature nor soil moisture showed a clear dominant association with SMU. These results should be interpreted as a descriptive classification of empirical patterns rather than as evidence of direct causal mechanisms. The regression analyses identify whether SMU covaries more strongly with soil temperature, soil moisture, or both within each ecosystem, but they do not exclude the influence of other environmental and biogeochemical factors such as soil texture, pH, nitrogen availability, vegetation type, substrate limitation, or microbial community structure. In the Southern Hemisphere, no consistent SMU seasonality was evident across most biomes (Fig. S7), which likely reflects sparse observational coverage, uneven monthly sampling, and the smaller land area represented in the database. Therefore, the biome-level classifications are most robust for ecosystems with adequate sample size and clear seasonal coverage, while patterns in data-limited regions should be interpreted with caution.

Monthly SMU exhibited pronounced heterogeneity across both temporal and spatial scales within and among sites, ranging from approximately 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 exceeded 10%, indicating moderate to high intra-annual variability and pronounced differences in seasonal SMU amplitude among biomes. The highest median monthly SMU occurred in August in shrublands, whereas the lowest occurred in November in subtropical deserts.

4 Future development and access to SMUD

4.1 Limitations of the current SMUD

The current literature search may not have captured all studies related to SMU, particularly those conducted in environments where SMU is intermittent or temporally variable, such as riparian zones, wetlands, and seasonally wet agricultural regions. Measurements reported in publications written in languages other than English or Chinese were not included in the database. Furthermore, the existing data structure could be further streamlined and automated to facilitate data access, reuse, and analysis.

The original SMUD database retains both positive CH_4 fluxes, representing uptake, and negative CH_4 fluxes, representing emissions. For the analyses presented in this manuscript, emission fluxes were excluded to focus specifically on SMU patterns. We note that this filtering affects the representation of net soil–atmosphere CH_4 exchange; therefore, users should interpret the analyses presented here primarily as reflecting SMU capacity rather than comprehensive net CH_4 exchange, likely overestimating the total SMU. In addition, although soil temperature and soil moisture are key drivers of SMU and are included in the current version of SMUD, other environmental factors, such as soil pH, C/N ratio, clay content, and other soil texture- or nutrient-related properties, are also known to influence CH_4 oxidation. These factors may regulate methanotrophic activity, gas diffusion, and substrate availability, and their effects on SMU may vary with spatial scale, biome type, and seasonal conditions. Therefore, the current version of SMUD is better suited for analyses of SMU patterns and their relationships with climate, seasonality, and soil hydrothermal conditions, but is less suitable for independently resolving the effects of intrinsic soil physicochemical controls. Future applications could address this limitation by linking SMUD with external soil datasets, thereby supporting more comprehensive assessments of climatic, hydrothermal, and edaphic controls on soil CH_4 uptake.

As new SMU studies continue to be published, additional data are continually emerging. We intend to maintain and periodically update a dynamic version of SMUD. Over time, we envision these updates evolving into a collaborative effort involving the broader research community, ultimately transforming SMUD 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 climate science. A global SMU database provides harmonized measurements of CH_4 fluxes and associated environmental drivers, together with standardized soil parameters, such as soil moisture and soil temperature, thereby supporting more robust bottom-up estimates of SMU. The database can also help process-based models represent SMU more mechanistically by providing observational constraints on CH_4 oxidation and its environmental controls, thereby reducing uncertainty in global SMU estimates, helping to 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, including tundra, boreal forests, savannas, and agricultural areas, the database helps reveal the spatiotemporal patterns of SMU and supports assessments of SMU responses to climate, vegetation, and land use (Dutaur and Verchot, 2007). Integrating point-based SMU observations with Earth observation products enables the upscaling of SMU estimates from local sites to regional and global scales (Oertel et al., 2016; Tian et al., 2016). The database further provides essential ground-truth observations 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, improve reproducibility, and enhance public trust. Moreover, version-control technologies developed within the open-source community enable "living" databases that can be continually updated, tracked, and improved by their users (Bond-Lamberty and Thomson, 2010). Thus, our goal is to build a global database of published SMU observations and provide it to researchers both as a citable 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 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). A detailed description of the data-processing workflow is provided in (Figure S9).

5 Conclusions

SMUD provides a comprehensive global dataset of SMU across both temporal and spatial dimensions. The database includes observations at four temporal scales—daily, monthly, seasonal, and annual—and spans a wide range of climatic zones and ecosystem types. Seasonal variation is essential for understanding intra-annual changes in SMU and elucidating its spatiotemporal patterns. The data reveal distinct SMU capacities among 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 observations, mainly published over the past three decades. In addition, the database aims 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 codes, and wrote the first draft. All authors contributed to data interpretation and preparation of manuscript text.

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