

Ecosystem-scale methane fluxes in terrestrial uplands diverge from soil-sink expectations

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Ecosystem-scale methane fluxes in terrestrial uplands diverge from soil-sink expectations

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40 Abstract

41 Upland terrestrial soils have traditionally been regarded as a consistent sink for atmospheric
 42 methane (CH_4) in the global budget (GMB), removing an estimated 11-49 Tg $\text{CH}_4 \text{ yr}^{-1}$. The
 43 inclusion of the terrestrial soil-sink as the dominant process describing the net atmospheric
 44 exchange of upland ecosystems relies on the key assumption that it equals the upland terrestrial
 45 budget. In this study, we used fluxes from 46 National Ecological Observatory Network tower sites
 46 across North America from 2021 to 2024 to characterize ecosystem-scale CH_4 exchange.
 47 Contrary to the terrestrial soil-sink expectation, 83% of upland sites exhibited net sources of CH_4
 48 annually ranging from +0.005 to +1.09 g C $\text{m}^{-2} \text{ yr}^{-1}$, while only 17% of sites functioned as net
 49 sinks (-0.05 to -0.21 g C $\text{m}^{-2} \text{ yr}^{-1}$). The upland ecosystem sink was, at best, ~48% of the assumed
 50 GMB soil sink and never reached the GMB estimate. The soil sink and the upland terrestrial
 51 methane budget are distinct quantities defined by different scales of inference and measurement
 52 domains. Assuming they are equivalent in the GMB is a scale-inference error—a scale mismatch
 53 between the measurement domain and the inference domain.

54 Introduction

55 Methane (CH_4) is the second most important anthropogenic greenhouse gas after carbon dioxide,
 56 with a global warming potential of ~28- 34 times that of CO_2 over a 100-year horizon ¹⁻⁵.
 57 Atmospheric methane concentrations have increased to more than 2.5 times their pre-industrial
 58 levels and continue to rise ⁶⁻⁸. Yet, substantial uncertainty remains in the relative contributions of
 59 natural and anthropogenic sources and the strength of the sinks that regulate the global methane
 60 budget ⁸. Among the most consistent features of the global CH_4 budget is the recognition that
 61 upland terrestrial soils —well-drained, aerated soils in elevated ecosystems that do not regularly
 62 experience flooding (~84- 105 M km^2 globally)⁹ — are a net sink for atmospheric CH_4 ¹⁰, removing
 63 an estimated 11 to 49 Tg $\text{CH}_4 \text{ yr}^{-1}$ through microbial oxidation in the soil ¹⁰⁻¹⁴. To represent the
 64 source contribution from upland terrestrial ecosystems in the global methane budget (GMB),
 65 terms are included for onshore geological processes (38 Tg $\text{CH}_4 \text{ yr}^{-1}$), wild animals (2 Tg CH_4
 66 yr^{-1}), termites (9 Tg $\text{CH}_4 \text{ yr}^{-1}$), and permafrost soils (1 Tg $\text{CH}_4 \text{ yr}^{-1}$) ¹¹. The role of vegetation as
 67 a source or sink is uncertain but is assumed to be small in upland ecosystems ¹¹. As a result, the
 68 soil sink is the representative flux for upland terrestrial ecosystems. It is the only terrestrial
 69 component included to oppose the dominant pattern of wetland emissions and meaningfully
 70 reduce atmospheric concentrations ^{15,16}. Our understanding of upland terrestrial fluxes, however,
 71 rests almost entirely on soil-chamber measurements, a foundation that may not represent the
 72 upland terrestrial budget ¹⁷⁻²².

73
 74 The case for the terrestrial soil CH_4 sink in the GMB was built through decades of soil-chamber
 75 studies conducted across forests, grasslands, shrublands, and croplands worldwide ²³⁻³¹.

Independent studies established that aerobic upland soils harboring high-affinity methanotrophic bacteria routinely oxidize atmospheric CH₄ at rates ranging from tenths to several mg CH₄ m⁻² d⁻¹ ^{32–35}. Chamber studies show CH₄ that soil moisture, temperature, texture, and land-use history modulate CH₄ uptake rates in consistent and predictable ways, providing a mechanistic basis for process-model representations of methanotrophy ^{36,37}. Regional and global extrapolations from these chamber studies, combined with process-models constrained by them, have converged on the view that terrestrial upland soils are a globally significant atmospheric sink, comparable in magnitude to some national-scale anthropogenic emission sources ³⁸. Confidence in this estimate comes not from any single measurement campaign but from the concordance of independent chamber-based studies across biomes and decades.

Despite noted support for the terrestrial soil-sink ^{10,12,39–42}, the inclusion of this sink term in the GMB rests on a key assumption that chamber fluxes represent ecosystem fluxes. Soil chambers sample gas exchange at the soil surface and, by design, definitionally exclude aboveground canopy-atmosphere exchange, lateral transport, and any non-soil biotic pathway. Chambers are also frequently deployed for short sampling periods under favorable logistical conditions, potentially undersampling episodic emission events associated with soil disturbance, freeze-thaw transitions, or precipitation pulses that may temporarily reverse net uptake ^{41,43}. Spatial heterogeneity in soil moisture, root density, and methanotroph community abundance, composition, and structure can cause plot-scale chamber means to diverge substantially from ecosystem-scale averages, and upscaling from a small number of chamber collars to ecosystem and regional budgets introduces compounding uncertainty ^{10,44}. These limitations do not invalidate chamber-based estimates of the terrestrial soil-sink. Instead, they suggest that the global upland terrestrial CH₄ net budget could differ substantially from the terrestrial soil-sink when including additional ecosystem components.

Eddy covariance and gradient-based micrometeorological methods offer a complementary perspective on CH₄ exchange by integrating flux signals over large footprints (typically 10⁴–10⁵ m²) that simultaneously encompass canopy, soil, and understory pathways. The rapid expansion of continuous ecosystem-scale CH₄ flux measurements, documented by the FLUXNET-CH₄ synthesis ^{45,46}, has confirmed the dominant role of wetlands as CH₄ sources at the ecosystem scale and revealed a diversity of flux behavior in upland systems that was not fully anticipated from chamber campaigns alone ^{44,47}. Studies at individual upland sites have reported weak net CH₄ emissions at the ecosystem scale under conditions where co-located chambers detected net uptake, suggesting that non-soil pathways, including plant-mediated production and transport or episodic lateral inputs, contribute to ecosystem-scale exchange in ways that chamber measurements miss ^{17,18,44,48–52}. More broadly, ecosystem-scale measurements at upland sites show different patterns in variability in the direction and magnitude of net CH₄ exchange than soil-sink studies ^{20–22,53–55}.

Differences in chamber-based expectations and ecosystem-scale observations raise a fundamental question: is the soil-sink an accurate characterization of the whole net methane budget in upland terrestrial ecosystems? Answering this question requires systematic characterization of ecosystem-scale CH₄ fluxes across upland ecosystems, sustained long enough to capture interannual variability and annual budgets. Assessments of this kind at the

ecosystem scale have been limited by three compounding factors: sparse tower representation across upland ecosystems^{56,57}, low signal-to-noise ratios in flux estimates^{58,59}, and instrument detection limits near the magnitude of typical upland fluxes⁵⁸. To improve inference despite these limitations, we computed CH₄ gradient fluxes (GF) from the National Ecological Observatory Network (NEON), which operates standardized tower installations at 47 sites spanning a broad range of North American ecosystem types, climates, and land uses⁶⁰. Although NEON sites include wetlands and croplands (n=5), most represent temperate upland terrestrial ecosystems (n=42). While site univariate representativeness is high for air temperature (99.9%), soil moisture (88.5%), mean annual precipitation (69.2%), aridity index (AI; 66.9%), and mean annual temperature (66.6%), only a small percentage of global upland areas have environmental conditions that are well represented by NEON sites (~4.5%; Supplementary Note1). Still, we use these data to characterize site-level exchange behavior, estimate annual net CH₄ budgets, and upscale NEON-trained relationships to global non-inundated terrestrial land area using ERA5 reanalysis meteorology to constrain the global implications. Our results provide the first multi-site, multi-year characterization of ecosystem-scale upland CH₄ exchange and suggest that ecosystem-scale measurements reveal a more complex picture of upland terrestrial CH₄ exchange rates than the terrestrial soil sink alone.

Results

Terrestrial Ecosystem CH₄ Fluxes

Although this study focused on upland ecosystems, we first show how gradient fluxes vary across all ecosystems represented by NEON sites (Fig. 1; n=46 sites). We defined exchange state classes (hereafter, state classes; weak-sources, weak-sinks, and fluctuating) based on the magnitude of annual CH₄ flux rates across ecosystems. Across all NEON sites, annual net CH₄ exchange was dominated by weak-sources (n=38 sites; 83%), with a smaller number of consistent weak-sinks (n=7 sites; 15%) and a single fluctuating ecosystem (Fig. 1a-b). Since most NEON sites were representative of terrestrial upland ecosystems (42 sites, 89% of all sites), non-upland or agricultural sites (i.e., wetlands and cropland) were either fluctuating or weak sources, and most upland sites (83%) were weak-sources.

Both forests and grasslands were distributed across state classes, and the fluctuating site was a wetland (BARR). At the 30-minute timescale, fluxes ranged from approximately -8 to +16 nmol C m⁻² s⁻¹ across all sites, with weak-sinks reaching their most negative instantaneous rates during the afternoon and evening hours. At the daily scale, weak-sinks ranged from approximately -0.9 to -4.5 mg C m⁻² d⁻¹ and source fluxes from +0.07 to +6.3 mg C m⁻² d⁻¹. At the annual scale, the timescale most relevant to global budget calculations, weak-sinks ranged from approximately -0.05 to -0.21 g C m⁻² yr⁻¹ (largest sink at GUAN, a tropical forest in Puerto Rico). In contrast, weak-sources ranged from +0.005 (HEAL, an Alaskan shrubland) to +1.09 (LAJA, a Puerto Rican grazed grassland) g C m⁻² yr⁻¹. ERA5-Land gap-filled annual flux estimates remained consistent with those derived from scaling the measured half-hourly record, confirming that ERA5-driven gap-filling did not systematically bias site-level annual exchange Fig. 1d). Additionally, within-

canopy storage was a negligible contributor to network-wide CH₄ budgets and state classifications. Regional upscaling results were robust to gap-filling uncertainty across NEON tower sites (Supplementary Note 2).



Fig. 1. Ecosystem flux state classes (i.e., weak-sink, fluctuating, and weak-source) and magnitudes for NEON sites by ecosystem type across (A) 30 min ($\text{nmol m}^{-2} \text{s}^{-1}$; balanced), (B)

daily ($\text{mg C m}^{-2} \text{ d}^{-1}$; balanced), and (C) annual ($\text{g C m}^{-2} \text{ yr}^{-1}$; balanced) temporal scales. Rows define state classes based on (D) ERA5 annual flux categories; columns show flux magnitudes across temporal scales. Bars show ± 1 SD. We summarized gradient fluxes (30-min, daily, and annual) in a balanced site-month-hour framework.

NEON sites were not distributed across global aridity conditions. While the global aridity index (AI) for upland cells ranged from 0.03 to 1950 and desert cells had an AI close to 0, NEON arid sites (JORN and SRER) had an AI of ~ 10.6 - 11.8 , which was roughly two to three orders of magnitude higher than deserts. NEON arid sites were closer to dry grassland/savanna than to a hyper-arid desert. Still, NEON's most arid sites were also classified as weak-sources with slightly positive observed fluxes, mean $\sim 0.026 \text{ g C m}^{-2} \text{ month}^{-1}$ and annual budgets of less than $0.5 \text{ g C m}^{-2} \text{ Y}^{-1}$. Even though NEON arid sites were relatively arid, they were not consistently dry enough to inhibit all CH_4 production and consumption. NEON sites were only distributed across weak-source and weak-sink classifications for forests and grasslands.

Diel and seasonal patterns of source probability

Across state classes, 30-minute CH_4 fluxes showed a pronounced diel structure (Fig. 2). Weak-sources maintained a source state throughout the day but exhibited slightly elevated emissions during nighttime and early morning hours. Weak-sinks showed near-zero or weak source fluxes at night and in the morning, transitioning to stronger net uptake in the afternoon and early evening. Peak sink rates were approximately $-12 \text{ nmol C m}^{-2} \text{ s}^{-1}$, occurring around hours 19 to 21. The fluctuating site showed no coherent diel signal, oscillating between source and sink states throughout the day. When expressed as the hourly probability of a positive (source) flux, the diel pattern further illustrated class-level differences (Fig. 2D). Weak-sources maintained source probabilities of 65-80% across all hours, with the highest probabilities during nighttime. Weak-sinks had source probabilities that declined through the day, falling below 50% during the afternoon in all months except winter. The fluctuating wetland site exhibited highly erratic hour-to-hour swings in source probability between 0% and 100%, consistent with a near-zero mean flux and high variance.

Seasonal variation in source probability was modest for weak-sources and weak-sinks relative to the between-class differences (Fig. 2E). Weak-sources maintained a source probability of approximately 65-70% throughout the year with no strong seasonal signal. Weak-sinks showed a slight summer reduction in source probability (dropping to $\sim 50\%$ in July). The fluctuating site exhibited extreme seasonal swings, rising to $\sim 93\%$ source probability in May and dropping to $\sim 20\%$ in August, driven by the dominance of a single site with limited data and high seasonal variability in atmospheric conditions.

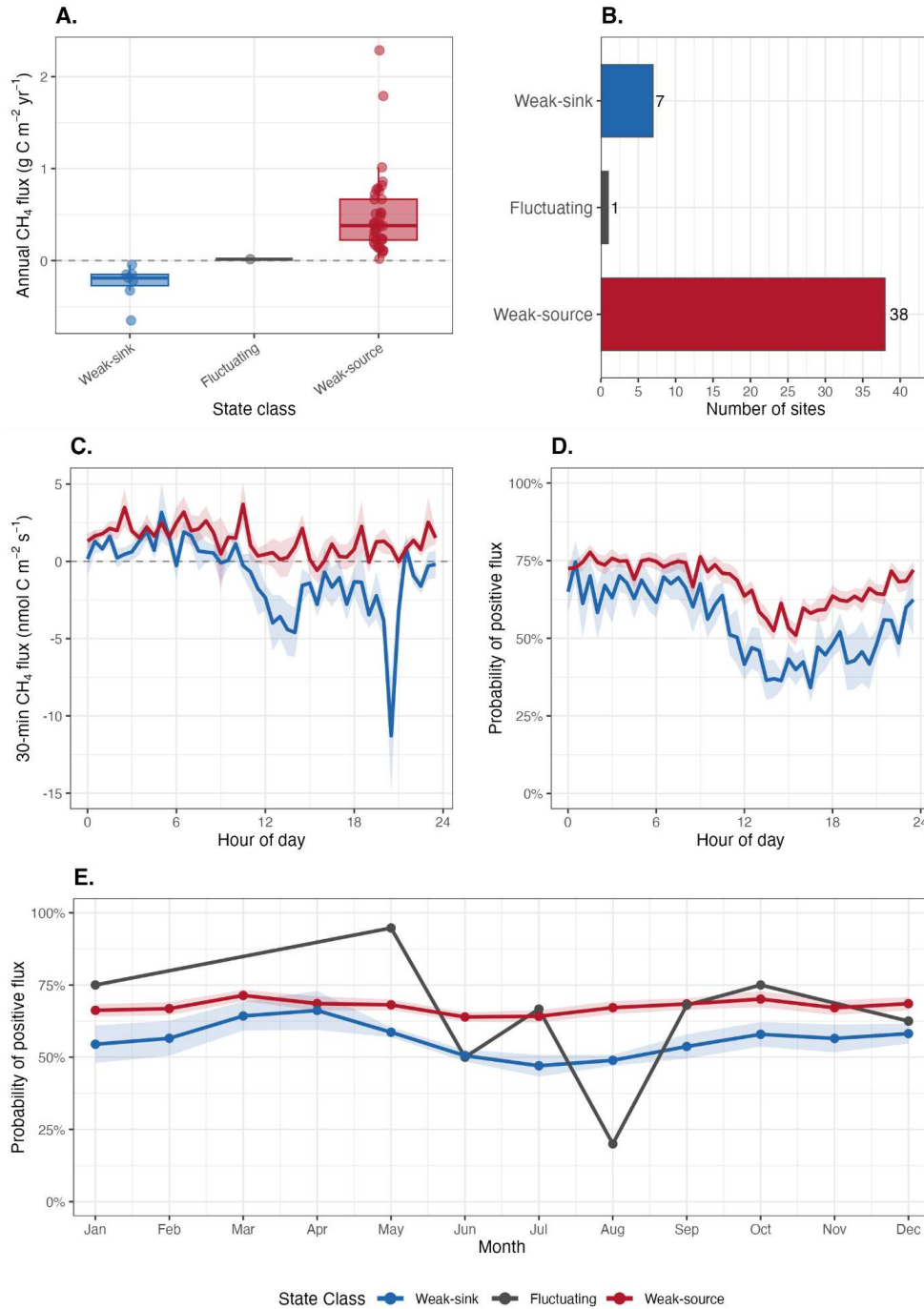
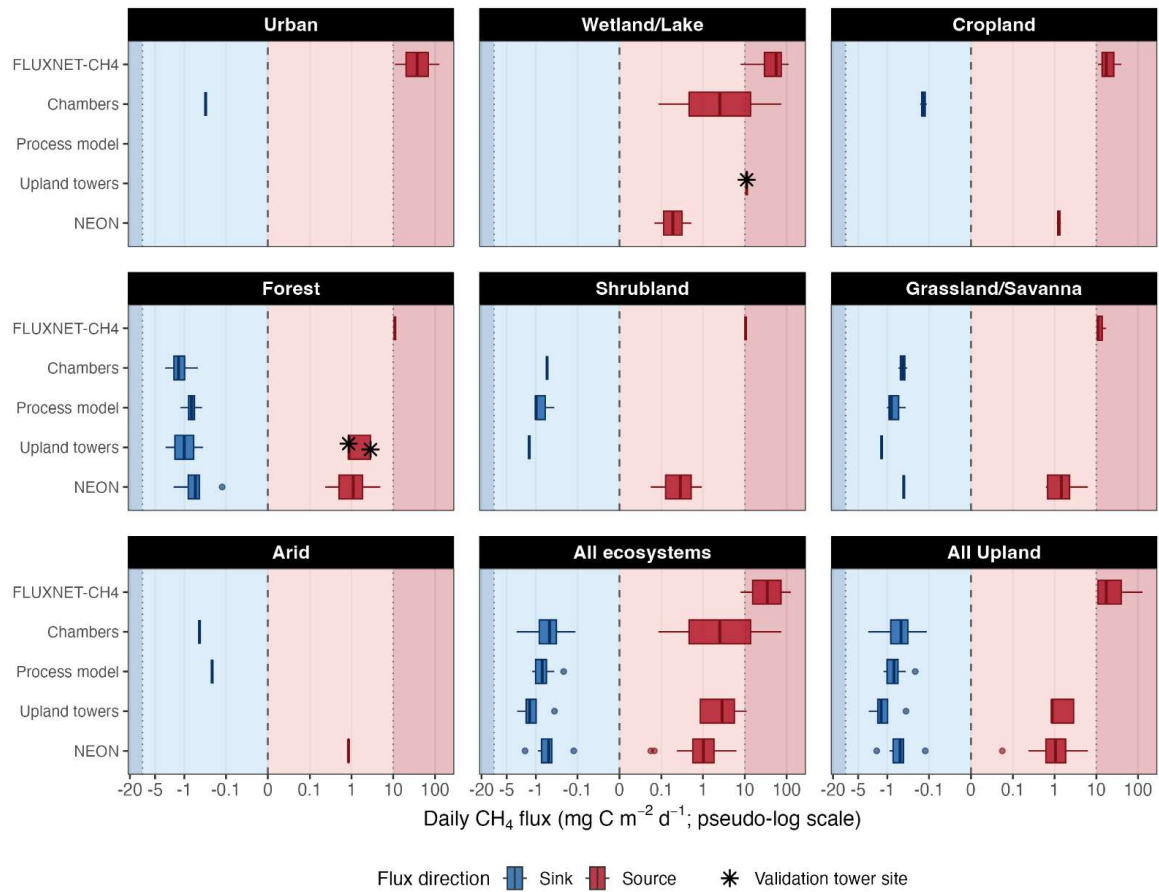


Fig. 2. Ecosystem CH_4 flux patterns for all NEON sites. (A) Sites were divided into state classes (i.e., weak-sink, fluctuating, and weak-source) based on their annual ERA5 flux magnitudes. The (B) number of sites in each state class, (C) the mean diel flux, and the source probability reveal dominant patterns across sites and states within a (D) day and (E) season. While flux magnitudes influenced the (C) diel flux patterns, source probability (D and E) revealed dominant patterns in the frequency of observed weak-source and sink patterns. The shaded regions are ± 1 SE.

Comparisons with published benchmarks

We compared ERA5-gapfilled NEON flux-gradient daily fluxes to published benchmarks from data sources that included FLUXNET-CH₄⁴⁵, chamber-based flux measurements from the literature and the soil methane uptake dataset (SMUD)^{24–26,28,30,32–35,41,61–71}, the process model Soil Methanotrophy Model (MeMo v1.0)³⁶, upland towers from the literature and SMUD^{20–22,53,54,72–76}, and individual validation-tower sites where we also compared gradient fluxes to EC (Supplementary Note 3). ERA5-gapfilled NEON flux-gradient daily fluxes fell within the range of published CH₄ exchange estimates for their respective ecosystem types (Fig. 3). For forests, NEON ERA5-filled sink estimates (-1 to -3 mg C m⁻² d⁻¹) were consistent with the range observed for chambers, MeMo, and upland tower measurements for temperate and boreal forests. In comparison, NEON forest weak-sources (~ 0.5 to 2 mg C m⁻² d⁻¹) overlapped with published EC measurements and validation tower estimates. For grassland and savanna sites, NEON weak-source fluxes (0.2 to 6 mg C m⁻² d⁻¹) were larger than the range reported for chamber measurements from comparable ecosystems, and the highest NEON values (LAJA, tropical humid grassland in Puerto Rico) approached the upper end of the reported range. Shrubland and wetland NEON sites also showed plausible magnitudes, with the wetland BARR site expressing near-zero fluxes consistent with upland-dominated tundra systems. Across all ecosystems, NEON fluxes did not systematically exceed or fall below published benchmarks, supporting the validity of the flux-gradient methodology and ERA5 gap-filling for estimating daily-to-annual CH₄ exchange at upland terrestrial sites (Supplementary Note 2-6). Yet, chamber fluxes peaked within the range of terrestrial weak-sinks, and EC tower (Including NEON towers) fluxes peaked in the range of weak-sources.

A.



B.

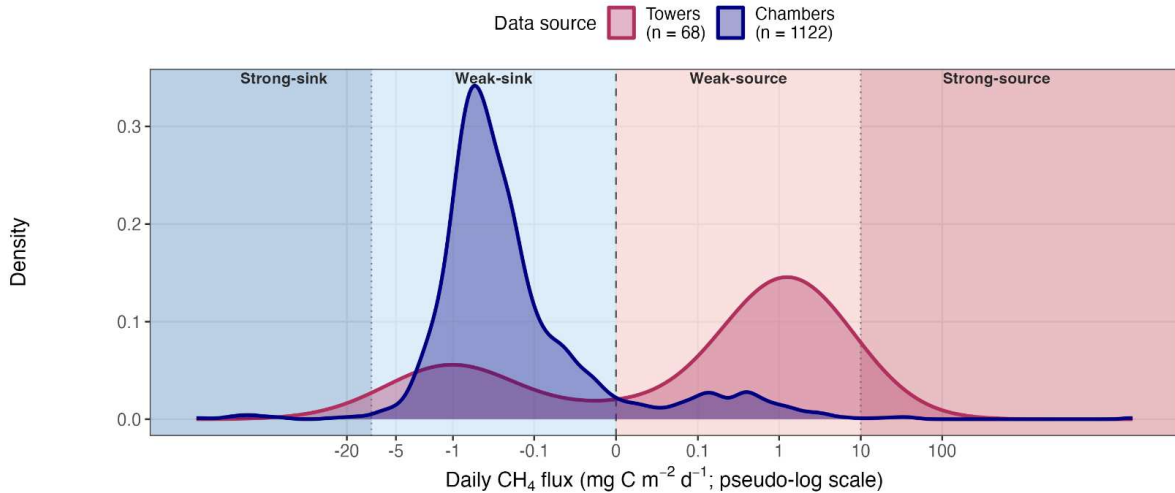


Fig. 3. (A) ERA5-gapfilled NEON gradient CH_4 fluxes compared with published CH_4 flux benchmarks across all ecosystems, upland and inundated. Rows represent data sources: FLUXNET- CH_4 ⁴⁵, chambers (published benchmarks + SMUD), a process model (MeMo v1.0), upland towers (published benchmarks + SMUD towers; individual validation-tower site values are marked with black stars; validation sites had co-located EC and gradient mixing ratio

measurements), and NEON towers (ERA5-gapfilled CH_4 budgets). Background shading divides each panel into four magnitude zones (i.e., strong-sink, weak-sink, weak-source, strong-source) separated at a shared $\pm 10 \text{ mg C m}^{-2} \text{ d}^{-1}$ threshold. The x-axis is pseudo-log transformed to accommodate the wide range of flux magnitudes across terrestrial ecosystem classes on a single scale. (B) The distribution of daily CH_4 flux rates for sites for upland chambers and all upland towers (NEON + published benchmarks). Positive values indicate net CH_4 emission to the atmosphere, and negative values indicate net CH_4 uptake.

We compared GF and EC fluxes at the validation towers to assess differences in ecosystem fluxes (Supplementary Note 3). Fluxes from the GF and EC produced similar implications for the validation sites. Reliability in tracking temporal dynamics showed an absolute uncertainty of $\pm 50\%$, as demonstrated convincingly at one site. The critical determinant of reliability was whether the selected pairs represented ecosystem fluxes, which was confirmed for CO_2 and H_2O at NEON site⁶⁰. Validation sites do highlight that differences between GF and EC fluxes can range from a factor of $0.5\times$ to $2\times$, indicating a potential bias in fluxes that should be incorporated into the uncertainty of upscaled fluxes. As a result, we scaled all gap-filled half-hourly fluxes by factors ranging from $0.5\times$ to $2.0\times$ and recomputed monthly and annual budgets for each site to assess whether biases in GF magnitudes would affect state classifications (Supplementary Note 4). Even under the most conservative scenario, in which fluxes were halved, all 38 upland sites retained their source classification. The network-median annual budget declined from $0.3 \text{ g C m}^{-2} \text{ yr}^{-1}$ at $1.0\times$ to $0.2 \text{ g C m}^{-2} \text{ yr}^{-1}$ at $0.5\times$. Still, it remained positive, indicating that the conclusion that the NEON upland sites were predominantly CH_4 -emitting was robust to magnitude uncertainty of at least a factor of 2. These results suggest that even substantial overestimation of gradient fluxes would not reverse the dominant source signal across the network (Supplementary Note 4).

Source Probability for Upland Terrestrial Ecosystems

To understand the magnitude of the upland terrestrial budget, we produced a spatial upscaling that estimates the net terrestrial sink using a two-stage random forest (RF) pipeline to upscale monthly CH_4 exchange to the ERA5 0.25° grid (2000-2025) using the global MODIS MCD12C1⁷⁷ annual land-cover product and the WAD2M inundation fraction⁷⁸. Stage 1 predicted the probability that a grid cell in a given month acted as a net CH_4 source ($P(\text{source})$). Stage 2 predicted the flux magnitude separately for source and sink states using two independent regression forests. We distinguished CH_4 source months from sink months with high fidelity (Fig. 4). Evaluated against out-of-bag predictions (OOB), the calibrated model achieved an area under the curve (AUC) of 0.92, a Brier skill score of 0.58 relative to the climatological base rate, and a Tjur R^2 of 0.58. At the 0.5 probability threshold, overall accuracy was 85%, sensitivity was 80%, and specificity was 91%. The asymmetry between sensitivity and specificity was consistent with the imbalanced prior probability of source months in the training record (78% source months). This asymmetry reflected the conservative balanced-sampling strategy, which deliberately traded sink-month recall for reduced overfitting. Isotonic calibration improved the reliability diagram for the raw OOB probabilities, reducing calibration error across all probability deciles. Permutation-based variable importance ranked mean annual precipitation (MAP) as the dominant predictor of source/sink state (importance = 39.3), followed by monthly air temperature (T_{air} ; 31.2), mean

annual temperature (MAT; 31.0), aridity index (AI; 29.5), monthly soil water content (VSWC; 18.7), and ecosystem type. The primacy of long-term mean climate descriptors (MAP, MAT, aridity) over interannual drivers (T_{air} , VSWC) suggests that the global distribution of CH_4 source and sink months was largely controlled by background aridity and thermal regime rather than by year-to-year climate variability.

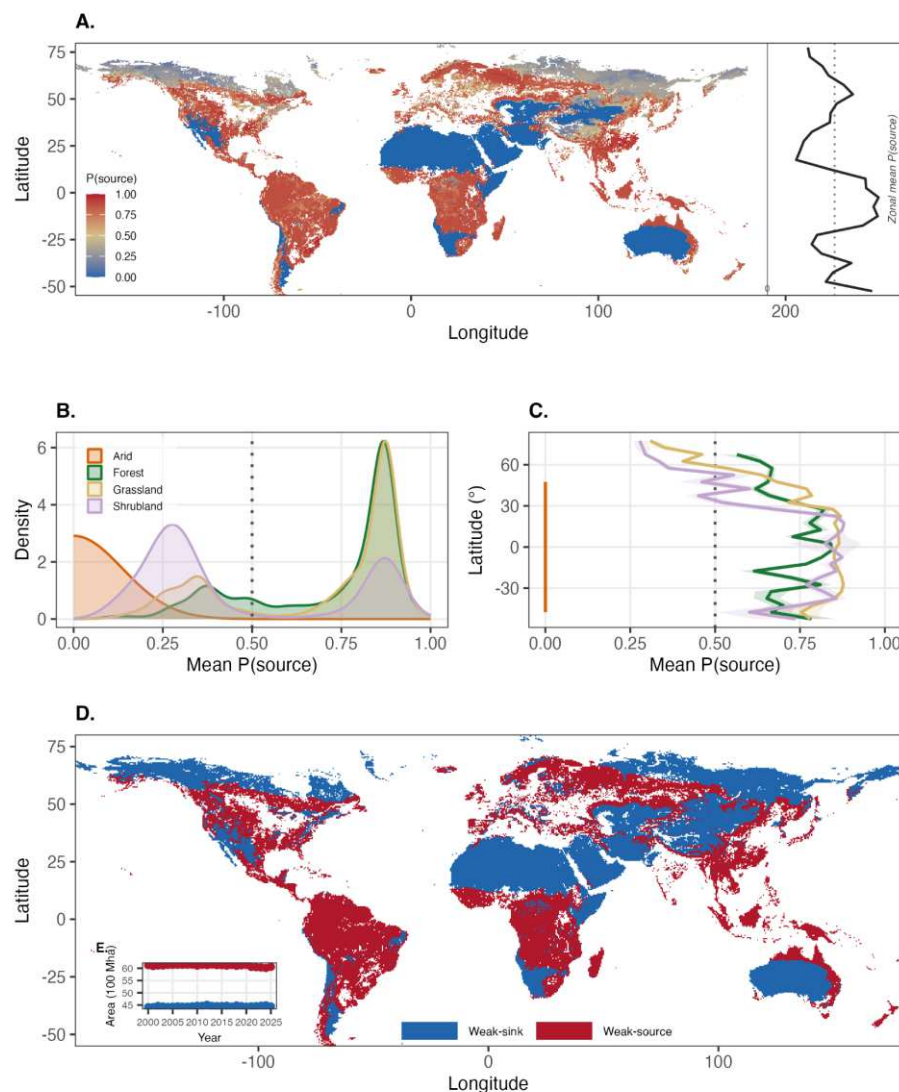


Fig. 4. Upland terrestrial monthly CH_4 source probability showing (A) continuous patterns in 2025 and the zonal mean along the latitudinal gradient. The source probability differed by (B) terrestrial ecosystem type and (C) by ecosystem type across the latitudinal gradient. We used the (D) mean annual probability to define the dichotomous source probability for cells containing upland ecosystems in 2025 and (E) from 2000–2025. Model projections were monthly, and the average annual probability for this figure classified the annual dichotomous patterns. The source probability model was only projected for cells containing upland terrestrial ecosystems.

The spatial projection of the P(source) for 2025 revealed a strong latitudinal gradient (Fig. 4B). Tropical shrublands, forests, and grasslands had the highest source probability for CH₄, while boreal forests, temperate shrublands, and arid regions exhibited lower mean P(source), consistent with their role of having a stronger sink potential for atmospheric CH₄ or near-neutral exchangers. The dichotomous classification ($P^* = 0.5$) assigned approximately 5,600 Mha of global upland terrestrial land area as net source and 4,900 Mha as net sink in 2025 (Fig. 4D). Both source and sink areas show minimal interannual variability from 2000 to 2025 (coefficient of variation < 1%), indicating that the global pattern of CH₄ exchange state was robust to interannual ERA5-Land climate fluctuations and was instead governed primarily by the fixed spatial distribution of MAP, MAT, and ecosystem type.

Upland Terrestrial CH₄ Magnitude

In Stage 2, we predicted flux magnitude separately for weak-sink and weak-source states (Fig. 5). Since Pearson correlation measures co-variation rather than agreement, we evaluate the models with Lin's concordance correlation coefficient (CCC; where the accuracy factor C_b penalizes departures from the 1:1 line) together with mean bias and RMSE. Within-sample (OOB), the log-magnitude RFs reproduced observed monthly magnitudes moderately well: for weak-sink months, CCC = 0.52 ($r = 0.68$, $C_b = 0.76$), RMSE = 0.03 g C m⁻² month⁻¹, and bias = 0.010 g C m⁻² month⁻¹ against a mean observed magnitude of -0.03 g C m⁻² month⁻¹; for weak-source months, CCC = 0.72 ($r = 0.82$, $C_b = 0.88$), RMSE = 0.04 g C m⁻² month⁻¹, and bias = -0.009 g C m⁻² month⁻¹ (mean observed = 0.05 g C m⁻² month⁻¹). The correlations exceed the CCCs because both models compress predictions toward the mean, with observed-on-predicted slopes of 0.35 (sink) and 0.51 (source). Under leave-one-site-out (LOSO) validation, the magnitude skill largely collapsed. The CCC fell to 0.09 for weak-sink months ($r = 0.20$, $n = 420$ across 28 unseen sites) and 0.08 for weak-source months ($r = 0.14$, $n = 1,464$ across 40 unseen sites), with observed slopes near zero (0.05-0.07), indicating that at an unseen site the models predict close to the training-mean magnitude. The RMSE increased only modestly to 0.04 and 0.06 g C m⁻² month⁻¹ because the small typical magnitudes dominated it. The LOSO error was comparable to the observed standard deviation (normalized RMSE ~ 1.1), suggesting it understated the skill loss that CCC and the flattened slopes revealed. The mean bias grew to 0.02 g C m⁻² month⁻¹ for the weak-sink and -0.02 g C m⁻² month⁻¹ for the weak-source out-of-sample. The models under-predicted the magnitude of both uptake and emission at sites they had not seen.

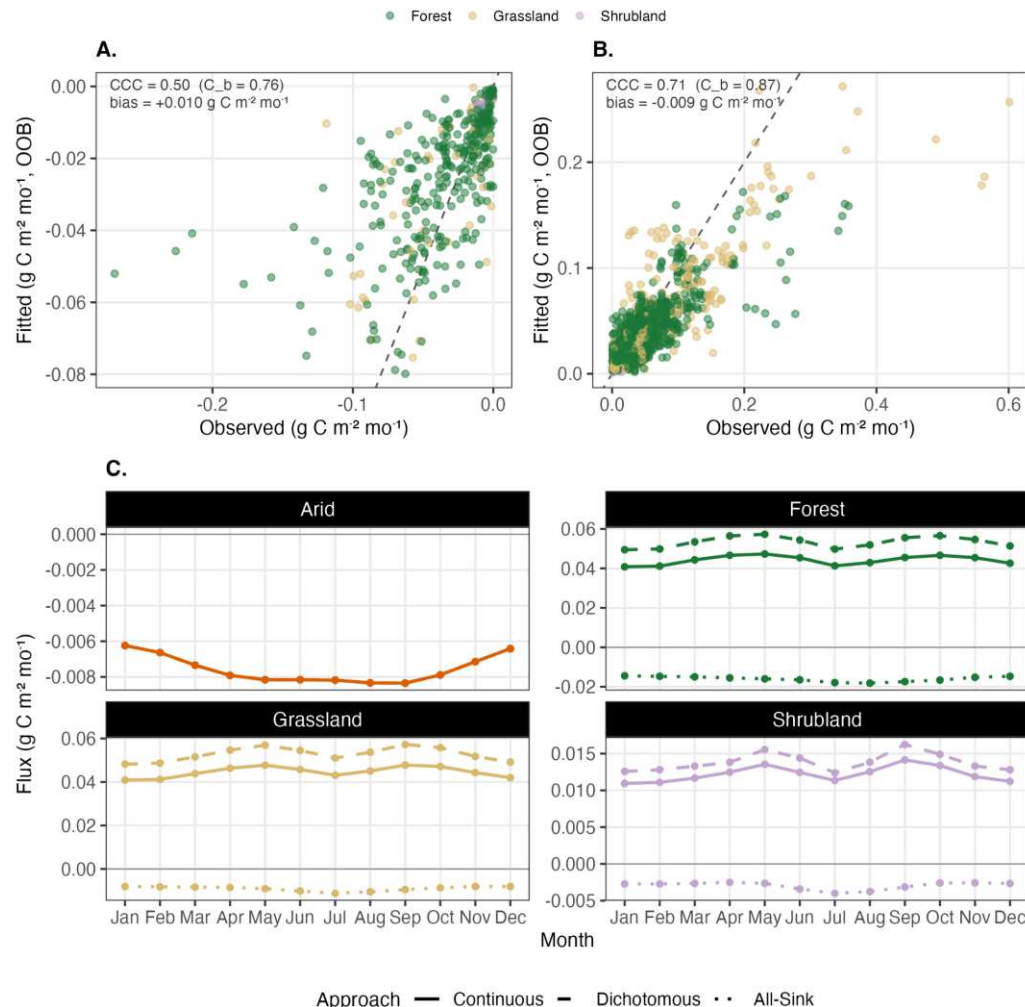


Fig. 5. Upland terrestrial monthly flux magnitude model performance and seasonal flux cycles. (A) Observed vs. fitted monthly CH₄ flux for the weak-sink magnitude model and (B) observed vs. fitted monthly CH₄ flux for the weak-source magnitude model. (C) Area-weighted flux cycle by ecosystem type under all three upscaling approaches (Continuous, solid; Dichotomous, dashed; GMB-Dichotomous, dotted).

Global terrestrial upland CH₄ budgets

The mean annual net terrestrial upland CH₄ exchange from 2000 to 2025 differed substantially across the three upscaling approaches (Table 1; Fig. 6). The All-Sink approach, which represents the theoretical maximum sink capacity of upland terrestrial ecosystems, yielded a mean annual budget of -16.7 ± 0.4 Tg CH₄ yr⁻¹ (48% of the GMB soil sink estimate). The continuous approach, which weighted source and sink magnitudes by the calibrated P(source) probability, estimated a mean net flux of 44.0 ± 0.4 Tg CH₄ yr⁻¹, indicating that probabilistic source weighting resulted in a net global source when integrated over the full land area. The dichotomous approach, using a 0.5 threshold, yielded the

largest positive flux ($50.2 \pm 0.4 \text{ Tg CH}_4 \text{ yr}^{-1}$). The divergence between the continuous and dichotomous estimates highlights the sensitivity of upland terrestrial CH_4 budget calculations to how cells with intermediate source-probability values are treated.

All three approaches were far from the mean annual GMB upland terrestrial soil-sink estimate of $-35 \text{ Tg CH}_4 \text{ yr}^{-1}$. A systematic threshold sensitivity analysis, sweeping P^* from 0.30 to 0.99 in the dichotomous framework, showed that the global budget monotonically decreased (became more negative) from 54.4 Tg at $P^* = 0.30$ to a floor of -16.5 Tg at $P^* = 0.99$. The GMB soil-sink estimate was not met at any source-probability threshold, indicating that the discrepancy between the upland terrestrial budget estimates and the GMB soil-sink estimate cannot be resolved by adjusting the source-probability threshold alone.

Table 1. Upland terrestrial mean annual CH_4 budget (2000-2025) under the three flux-expression approaches. Values are mean $\pm 1 \text{ SD}$ across years. The percentage of the GMB-soil sink is relative to the mean annual GMB upland soil-sink estimate of $-35 \text{ Tg CH}_4 \text{ yr}^{-1}$, and the uncertainty associated with gradient flux (GF) magnitudes.

Approach	Mean ($\text{Tg CH}_4 \text{ yr}^{-1}$)	SD	% of GMB-soil sink	GF magnitude Uncertainty
All-Sink	-16.7	± 0.4	47%	± 8.2
Continuous	44.0	± 0.4	130%	± 22.7
Dichotomous	50.2	± 0.4	157%	± 27.4

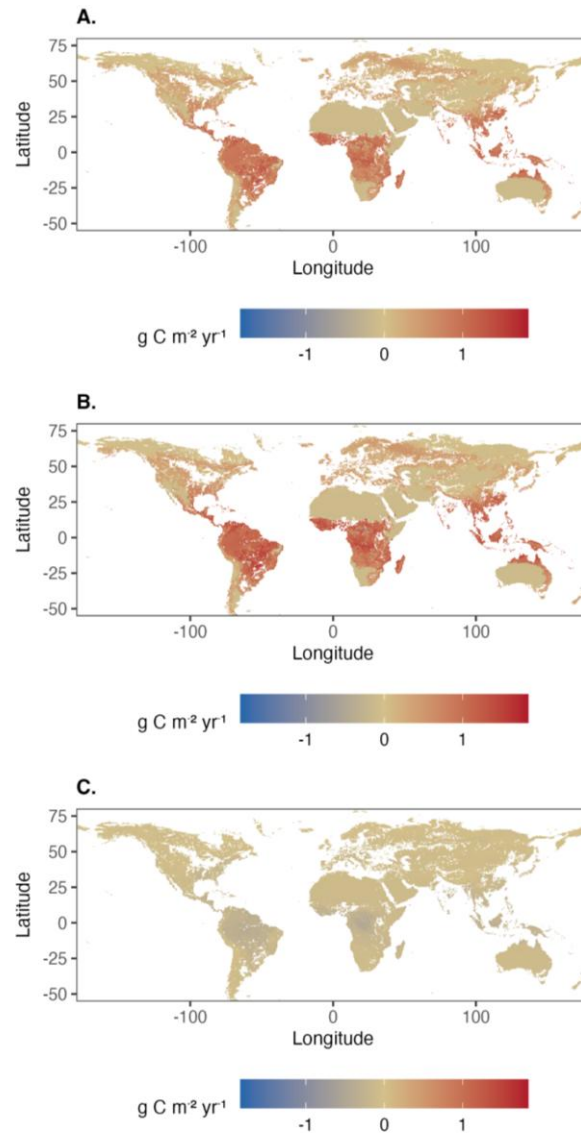


Fig. 6. Upland terrestrial annual net CH_4 flux maps for 2025 under three upscaling approaches: (A) continuous, (B) dichotomous, and (C) GMB-dichotomous. All panels show annual net upland CH_4 exchange ($\text{g C m}^{-2} \text{yr}^{-1}$), with a common symmetric range across panels.

We explored the sensitivity of the global upland terrestrial CH_4 budget to gradient flux magnitude bias (Supplementary Note 5) by applying multiplicative $\pm 50\%$ corrections uniformly to all ERA5-upscaled annual budgets across three modeling approaches (e.g., All-Sink, Continuous, and Dichotomous). The sign and broad magnitude of the upscaled source estimate were insensitive to systematic gradient flux biases within the tested range, and the conclusion that upland NEON terrestrial ecosystems constitute a net CH_4 source was robust to flux-magnitude uncertainty on this scale. Globally, upland terrestrial ecosystems were a net source of CH_4 ($\sim 22\text{--}75 \text{ Tg CH}_4$) to the atmosphere.

Discussion

The upland terrestrial methane budget differs from the terrestrial soil-sink

Ecosystem-scale results were at odds with the idea that the terrestrial soil-sink is representative of the upland terrestrial budget. The frequency of weak-sink conditions suggests that CH_4 production was not negligible, that CH_4 oxidation did not always dominate production, and that inferences from the benchmark net chamber fluxes did not represent the upland terrestrial ecosystem. The gap between the soil-sink and net upland terrestrial budget reflects omitted atmospheric CH_4 sink/source mechanisms, limited spatial coverage of training sites, and/or uncertainties in the GMB partitioning itself. While ecosystem and soil fluxes were in similar ranges, upland terrestrial ecosystem fluxes were skewed towards weak-sources while chambers were skewed towards weak-sinks. To some degree, we recognize that distributional differences may also be affected by the limitations of ecosystem measurements⁵⁸, though this would not fully explain the discrepancy. Ecosystem and landscape studies have extensively attributed differences between chambers and towers to micro-topography within upland ecosystems that produce soil moisture gradients and microsite hot/cold spots^{20,22,53,54,79,80}. While chambers sample "representative" spots, they do not necessarily capture these gradients. Differences in the magnitude of weak-sinks and weak-sources suggest that even wet patches within footprints could change the state of ecosystems. The mean weak-source magnitude is $\sim 1.38 \text{ mgC m}^{-2} \text{ d}^{-1}$, which is about twice the mean sink magnitude ($-0.68 \text{ mgC m}^{-2} \text{ d}^{-1}$). A weak-sink could flip to a weak source with just a 0.33 inundation fraction. Terrestrial ecosystems are currently measured and modeled at scales of 0.5–50 km, leaving the microsites that govern fine-scale fluxes unresolved and necessitating approaches that account for this limitation.

Still, it is important to note that we do not challenge the existence of a terrestrial soil-sink. We instead show that weak-sink behavior is not consistently observed at the ecosystem scale, which supports documented cases of plant-mediated transport, wet microsites⁸¹, and episodic inputs that contribute to ecosystem-scale exchange^{17–19,49–52,82}. The results presented here raise a question that extends well beyond the scope of any single measurement network: what are the implications if the upland terrestrial CH_4 budget is not equal to the soil-sink, or if upland terrestrial systems are, in net, a source rather than a sink of CH_4 to the atmosphere? If the relationships observed across NEON ecosystems hold globally, upland terrestrial ecosystems are likely a global source of CH_4 to the atmosphere. Adjusting the GMB for upland terrestrial ecosystems is not simply a matter of revising a single budget term. It would require a fundamental reassessment of how global CH_4 budgets are constructed, how process-based models are parameterized, and how we project the methane-climate feedback over the coming century.

Source attribution in the Global Budget

The top-down GMB is anchored by directly observed atmospheric CH₄ concentrations ¹¹, so any revision to one budget component must be compensated elsewhere. Current bottom-up and top-down syntheses estimate that upland terrestrial soils remove approximately 11- 49 Tg CH₄ yr⁻¹ from the atmosphere ¹⁰⁻¹⁴. If the terrestrial upland budget were substantially different than the soil-sink, then one of three adjustments would be necessary in the GMB budget: anthropogenic or natural CH₄ sources are currently overestimated, another unrecognized or underestimated sink exists, or atmospheric CH₄ growth is being sustained by a larger net imbalance than current budgets acknowledge. Since the atmosphere integrates all surface fluxes, the components of the global budget must still close, requiring an adjustment to the terrestrial budget to explain changes in the atmosphere. The location and nature of that resolution would reshape our understanding of which sectors and processes dominate the current imbalance between CH₄ sources and sinks ⁸³⁻⁸⁵.

Scaling from NEON towers and the structural bias of chamber-calibrated models

If all upland terrestrial ecosystems are treated as sinks, the sink magnitude was only -16.7 Tg CH₄ yr⁻¹, which was 48% of the GMB soil-sink. The upscaling analysis presented here suggests that ecosystem-scale net CH₄ exchange in upland terrestrial ecosystems may not be consistently negative, and that the spatial distribution of source and sink states may depend strongly on the assumptions embedded in the upscaling approach. These results do not require upland ecosystems to be major CH₄ sources in absolute terms. Even near-zero ecosystem-scale fluxes, if they systematically offset the soil oxidation signal, would be sufficient to erode the apparent terrestrial sink substantially. A globally distributed network of ecosystem-scale flux measurements would be needed to confirm whether this pattern is robust across biomes and climate zones ^{56,57}. In the interim, the differences between plot-scale chamber observations and ecosystem-scale flux distributions suggest a structural rather than a parameter problem in current models ^{17,18,49-52}.

Process-based models built and calibrated on decades of soil-chamber flux data are likely to carry the limitations of that measurement basis into their global projections, largely because the terrestrial soil sink is not equal to the terrestrial CH₄ budget. If chambers preferentially observe the oxidation-dominated portions of ecosystems ⁸⁶, then models trained on those observations will systematically overestimate methanotrophy at the landscape scale. Aboveground pathways a ground chamber can't see (tree stems/woody surfaces, deadwood, canopy) have been long ignored because woody CH₄ exchange was assumed to be zero ^{17,17,19,49,51,52,82}. At the same time, closed-chamber deployments miss cryptic methanogenesis in anaerobic microsites, plant-mediated transport from deeper soil layers, and lateral CH₄ redistribution via groundwater and hydrological connectivity, and models calibrated to them are correspondingly underrepresented. The result is a class of models that are internally consistent with their training data but may be structurally biased with respect to the full suite of ecosystem pathways that determine net CH₄ exchange at the scales relevant to regional and global budgets. Advancing models to account for the full upland terrestrial budget would require not just updated parameter values but revised model architectures that can represent the full vertical and lateral extent of CH₄ production, transport, and oxidation within an ecosystem.

Methane-climate feedbacks and the regulating capacity of upland soils

The terrestrial soil-sink has additional significance beyond its magnitude: it is commonly treated as a negative feedback on atmospheric CH₄ accumulation because higher atmospheric concentrations are expected to stimulate greater microbial oxidation and, therefore, larger uptake rates³⁷. If the net terrestrial sink is weaker than assumed, this buffering capacity may be proportionally smaller. The consequences would compound over time. A reduced sink could imply that the effective atmospheric lifetime of CH₄ is longer than typically estimated, since a smaller fraction of emitted CH₄ is removed per unit time by terrestrial oxidation. In turn, future increases in CH₄ emissions from warming-induced wetland expansion, permafrost thaw, or agricultural intensification would produce larger atmospheric accumulation than models calibrated to the current soil-sink magnitude would project. Climate projections that rely on these models may therefore underestimate CH₄ accumulation under warming scenarios, potentially underestimating the radiative forcing contribution from CH₄ and overestimating the terrestrial biosphere's capacity to offset anthropogenic emissions through uptake.

What we measure at chambers and towers is only the net of gross CH₄ production and gross oxidation occurring simultaneously. A near-zero net sink can mask small-minus-small or large-minus-large gross terms, which respond very differently as the climate warms. Therefore, a weak-sink cannot be assumed to be a stable buffer. Just as we partition CO₂ net exchange into gross primary productivity and respiration because different processes drive them, methane requires resolving its gross terms through incubations, isotopes/pool-dilution, and microbial measurements^{68,87}, rather than relying solely on additional net-flux observations.

Taken together, these considerations argue for treating the upland terrestrial CH₄ sink as an open empirical question rather than a settled budget component. Resolving it will require sustained, ecosystem-scale CH₄ flux measurements across a range of biomes and climate states; methods that can attribute ecosystem-scale exchange to specific mechanistic pathways; and budget frameworks that formally integrate the different spatial and temporal scales at which chambers, towers, and atmospheric inversions operate.

Upland terrestrial ecosystems are underobserved for two reasons: research and tower networks have historically focused on high-emission wetlands, and the near-zero fluxes typical of uplands can only be resolved by high-precision, closed-path sensors. The ecosystems most in need of measurement are exactly where the available instruments perform worst. Closing this gap, therefore, requires not just more sites but the right sensors. We need higher-resolution, lower-cost instruments that can resolve near-zero exchange without the power demands and expense of current designs. While the NEON gradient-flux dataset represents a major step in understanding upland terrestrial ecosystems, its North American-centric sample and relatively short measurement record mean the global picture remains incomplete. The most important contribution of this analysis may be to demonstrate that the assumption of an upland terrestrial CH₄ soil sink warrants sustained scrutiny at the ecosystem scale before it is embedded as a fixed term in the next GMB.

Methods

Study Sites

The NEON (Fig. 7) has uniform micrometeorological instrumentation at 47 terrestrial sites across the United States. Sites represent a wide diversity of ecoclimate regions and canopy structures^{88–90}. Forests account for 62% of towers (29 towers) and include tropical, temperate, boreal, and savanna forests. Short-stature ecosystems include shrublands (5 towers) and grasslands (9 towers). While most towers represent upland ecosystems, they also include temperate wetlands and croplands. Within this wide variety of ecosystem types, canopy heights range from 0.15 to 53 meters, plant rooting depths vary widely⁹¹, soil mineralogies vary⁹², and soil organic carbon ranges from 2 to 50 kg C m⁻²⁹³. We used the NEON IGBP classes and site descriptions defined for each tower's footprint in their AmeriFlux metadata. We classified each site into one of four ecosystem types used throughout the analysis: forest, grassland, shrubland, and arid. We excluded wetlands and cropland towers from specific assessments of upland terrestrial ecosystems.

To confirm that NEON sites were upland ecosystems, we also explored inundation fraction at tower sites using the WAD2M⁷⁸. The mean inundation fraction across cells containing tower sites was very low (~0.023, i.e., ~2%), confirming these were genuinely upland/dryland cells. A few sites had seasonally meaningful maximum inundation: TOOL (0.49), HARV (0.33), UNDE (0.24), NOGP/DCFS/WOOD (~0.22). At these sites, periodic wetness had a high potential to influence the flux signal within footprints. However, the WAD2M had a much coarser resolution and did not directly explain conditions within footprints or identify which sites were most likely to have higher fluxes (Supplementary Note 7).

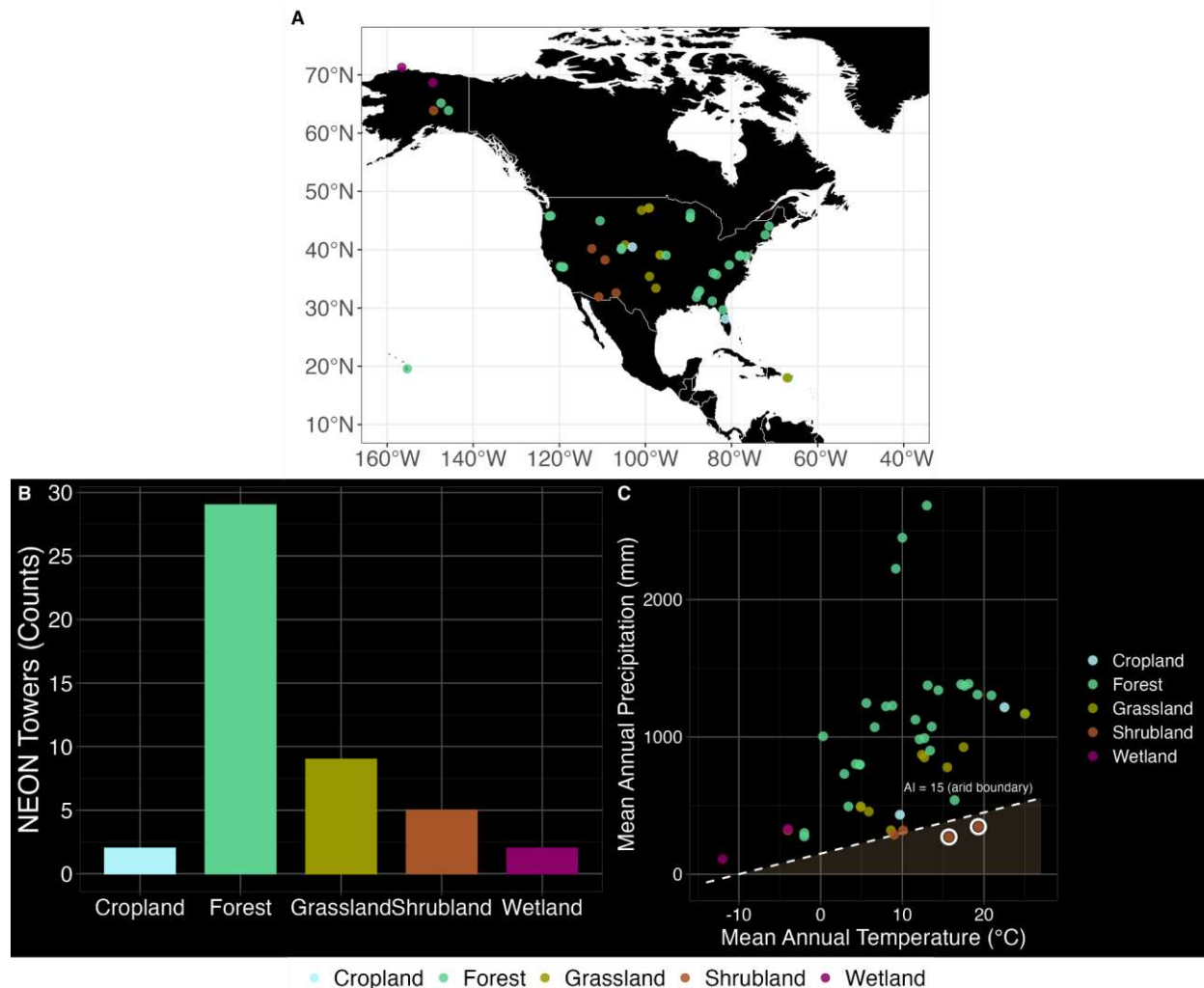


Fig. 7. The NEON study sites. **(A)** Geographic distribution of NEON tower sites across North America, colored by ecosystem type. **(B)** The number of towers per ecosystem type. **(C)** Climate space of study sites plotted as mean annual precipitation (MAP) versus mean annual temperature (MAT), colored by ecosystem type. The dashed white line marks the de Martonne Aridity Index threshold of $AI \leq 15$; sites below this line (white outlines) were classified as arid.

Instrumentation (NEON Towers)

We obtained NEON tower data from 2021 to 2024. Fluxes of CO_2 ($\mu\text{mol m}^{-2} \text{s}^{-1}$), latent heat flux (W m^{-2}), sensible heat flux (W m^{-2}), and friction velocity, u^* (m s^{-1}) were measured using a fast-response gas analyzer (LI-COR - LI7200) and sonic anemometer (Campbell Scientific CSAT-3) at 20 Hz at the top of the towers. We processed eddy covariance data on a 30-minute timescale following NEON protocols⁹⁴, with data de-spiking^{95,96}, planar-fit coordinate rotation⁹⁷, and corrections for the infrared gas analyzer⁹⁸, time lag⁹⁹, sonic temperature¹⁰⁰, and high-frequency spectral loss¹⁰¹. Data were also filtered using the NEON final QA/QC flag, which integrates the

results of multiple automated QA/QC assessments, including statistical plausibility, sensor diagnostics, and assumptions of the underlying measurement theory (e.g., stationarity and development of turbulence for eddy covariance fluxes). In addition to automated screening, NEON scientists conduct manual data reviews to identify known sensor or site-specific issues. Observations assigned a science review flag (FinalQFSciRvw = 1) were considered suspect and excluded from further analyses. This filtering procedure follows NEON-recommended practices and ensures that subsequent analyses are based on the highest-quality observations available.

Meteorological data included aspirated air temperature (Thermometrics Climate RTD 100 Ω Probe) and horizontal wind speed and direction (Gill Wind Observer II) at multiple profile heights at each site. Atmospheric pressure P (kPa; Vaisala PTB 330) and relative humidity (Vaisala HMP 155) were measured at the mid-tower and the tower top, respectively. We measured dry-air mixing ratios of CO₂ ($\mu\text{mol mol}^{-1}$) and H₂O (mmol mol^{-1}) at multiple profile heights at each site using a Picarro G2131-i NEON-specific analyzer with additional upgrades to the CH₄ channel. We measured CH₄, CO₂, and H₂O at nominal rates of 1 Hz for CO₂ and H₂O and 0.1 Hz for CH₄. We calculated the means and variances of calibrated mixing ratios at each sampling level (6-minute sampling periods). Air was sampled from inlets at each tower sampling level, starting at the top and proceeding to the next lower inlet until reaching the bottom, then returning to the top.

The NEON towers use high-accuracy sequential sampling over the tower profile. The mixing ratio pairs used for gradient differences spanned at least 20 minutes and had a 10-minute dwell time per sampling level (4-min transition, 6-min sampling for H₂O and CO₂; 1-min transition, 9-min sampling for CH₄), with some pairs spanning multiple canopy levels. Although sequential sampling is less than ideal, studies have shown that only minor errors are introduced into flux measurements when a single analyzer measures at alternating heights in a non-simultaneous manner^{102–105}. Meteorological data were available as 1- or 2-minute averages, depending on the variable, and we used the shortest available duration. We aligned meteorological variables with the paired concentration measurement window by averaging them over the 20-minute sampling window. This approach, using linear regression for large time delays, has been used in other studies¹⁰⁶. Turbulent flux measurements reported as 30-minute averages were filtered using NEON's final quality flag before linearly interpolating to the time midpoint of the combined sampling window's observed paired-level gradient mixing ratios. Additionally, because of interpolation, we could calculate GFs only when both the preceding and succeeding half-hourly eddy covariance fluxes were available. We downloaded all data using the *neonUtilities* package in R (Table 2).

Table 2. We used data from the National Ecological Observatory Network (NEON). This continental-scale research platform collects long-term, open-access data on animals, soil, water, and the atmosphere across the U.S. to understand how ecosystems are changing.

Data Product	NEON Product ID	Reference
Relative Humidity	DP1.00098.001	¹⁰⁷
2D wind speed and direction	DP1.00001.001	¹⁰⁸
Photosynthetically active radiation (PAR)	DP1.00024.001	¹⁰⁹
Bundled Eddy Covariance	DP4.00200.001	¹¹⁰
Soil physical and chemical properties, Megapit	DP1.00096.001	¹¹¹
Root biomass and chemistry, Megapit	DP1.10066.001	¹¹²

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562 Gradient Flux Method

563 While each NEON site has EC at the top of the tower for CO₂ and H₂O, only CH₄ concentration
564 profiles extend down into the canopy. Using the GF method, which has been shown to provide
565 reliable estimates of CO₂ and H₂O, we can estimate ecosystem CH₄ fluxes. The GF method can
566 significantly enhance our understanding of the complexities of ecosystem exchange rates by
567 utilizing instrumentation at existing tower sites that measure CH₄ concentrations at different heights
568 ^{74,76,113,114}. The GF method uses the concentration difference measured at two heights and the
569 assumption that scalar turbulent transfer is analogous to molecular diffusion. The standard
570 approach is expressed as:

$$571 \quad F = -\rho_d K \frac{\partial C}{\partial z} \quad \text{Eq. 1}$$

572 where F is the target turbulent flux (e.g., CH₄), ρ_d is the dry air density (mol m⁻³), C is the scalar
573 dry air mixing ratio (μmol mol⁻¹) at height z (m), and K is eddy diffusivity (m² s⁻¹). Using dry air
574 mixing ratios eliminates density effects. One challenge of the gradient-flux method is
575 parameterizing the eddy diffusivity (K), which can be determined from Monin-Obukhov similarity
576 theory ¹¹⁵ or, as suggested by Miyata et al. (2000), from the friction velocity derived from a sonic
577 anemometer ¹¹⁶.

578 Modified Bowen Ratio

579 Fluxes were estimated following the modified Bowen ratio (MBR) approach (Eq. 2) by expressing
580 Eq. 1 for two fluxes, F_1 and F_2 , taking the ratio, leading K to cancel out, and rearranging to:

$$581 \quad F_2 = F_1 \frac{(\Delta C_2)}{(\Delta C_1)} \quad \text{Eq. 2}$$

582 where F_2 is the target flux, F_1 is a known flux, ΔC_2 is the target gas dry air mixing ratio difference
583 between two heights, and ΔC_1 is the known gas dry air mixing ratio gradient difference measured
584 across the same height profile. This approach assumes that eddy diffusivity is identical for both
585 the tracer (F_1) and the target gas (F_2). If F_1 is known from EC measurements, F_2 can be
586 determined ¹¹⁷. Using the MBR method removes the need to invoke Monin-Obukhov similarity for
587 different stabilities, keeping the physics simple. Previous studies have used these methods to
588 calculate ecosystem-scale fluxes for trace gases (e.g., methane ^{75,76}, hydrogen ¹¹⁸, carbonyl
589 sulfide ¹¹⁹, and mercury ¹²⁰.

The Aerodynamic Method

In the aerodynamic model, K is given as:

$$K = \frac{k u^* (z-d)}{\phi_h(\zeta)} \quad \text{Eq. 3}$$

where K is assumed to be the same for all variables (H_2O and CO_2), the von Karman constant (k) is 0.4¹²¹, u^* is the friction velocity and is measured by the fast-response turbulent flux data, z is the mean of measurement height calculated as the geometric mean between the two levels, and d is the displacement height. Canopy height (h) was calculated aerodynamically from the turbulence statistics¹²², and displacement height was estimated as $0.66h$. The $\phi_h(\zeta)$ is the stability correction function. It is the Obukhov stability parameter calculated as the ratio of effective height ($z-d$) and Obukhov length (L). ϕ_h is assumed to be equal to the stability correction function for CO_2 and H_2O , and is calculated as¹²³:

for $-5 < \zeta < 0$:

$$\phi_h = (1 - 16\zeta)^{-1/2} \quad \text{Eq.4}$$

for $0 \leq \zeta < 1$:

$$\phi_h = 1 + 5\zeta \quad \text{Eq.5}$$

The Obukhov length is given as:

$$L = \frac{-u_*^3 T}{kg(w'\theta'_v)} \quad \text{Eq.6}$$

where T is the surface air temperature measurement taken from the lowest tower height, g is gravitational acceleration (9.8 m s^{-2}), and θ_v is the virtual potential temperature.

The Wind Profile Method

The eddy diffusivity for the wind profile method (K_{wp}) was calculated at each tower level as:

$$K_{wp} = \frac{k^2 (z-d) \underline{u}}{\phi_h \ln \frac{z-d}{z_o}} \quad \text{Eq.7}$$

where k is the von Karman constant, $z-d$ is the effective height as calculated in the previous section, $\underline{u}$ is the average wind speed, and z_o is the roughness length estimated as $0.1h$.

Filtering Gradient Fluxes

Gradient fluxes were filtered using a signal-to-noise ratio (SNR) based on the difference in concentration (ΔC) of the target gas (Eq.8):

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$$SNR = \frac{|\Delta C|}{sd(\Delta C)}$$

Eq. 8

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$$F_{CH_4} = F_{Turbulent} + F_{storage}$$

Eq. 9

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We randomly sampled concentration measurements within the sampling period to estimate the standard deviation in ΔC . We used a conservative threshold of 3 at every site, based on the stabilization of the error between EC and GF for SNR values above this threshold. Depending on the technique, we required an SNR for both the target and tracer gases (TSNR) (MBR). There was only one NEON site (PUUM) where the low signal-to-noise ratio yielded insufficient gradient fluxes. In addition to filtering for SNR, we filtered GFs using the friction-velocity threshold (u^*) defined for each site by AmeriFlux¹²⁴ at the top of the towers. The u^* threshold indicated when shear-driven turbulent mixing was insufficient¹²⁴.

We calculated the GF ensemble as the median flux over a half-hour for reliable sampling height pairs and approaches⁶⁰. We used CH_4 fluxes to quantify ecosystem exchange rates in upland ecosystems. For each reliable half-hour estimate, we calculated the total flux as (Eq.9):

Where F_{CH_4} is the net methane flux for a half-hour, $F_{Turbulent}$ represents the turbulent gradient-flux estimate, and $F_{storage}$ accounts for temporal changes in CH_4 stored below the measurement height. Positive values were interpreted as net CH_4 sources to the atmosphere, and negative values were interpreted as net CH_4 uptake. Reliable observations were not uniform across sites, months, or times of day, so we did not classify site behavior based on raw row counts. Instead, we summarized observations in a balanced site-month-hour framework. We used F_{CH_4} observations to generate site-level CH_4 flux products at three temporal scales: standardized 30-min flux rates, gap-filled daily fluxes, and annual flux budgets.

For the mean 30-min ($\mu mol\ C\ m^{-2}\ s^{-1}$) flux product, gradient fluxes were first grouped by site, month, and half-hour of the day. We calculated mean F_{CH_4} within each site-month-half-hour bin. Monthly site means were then calculated by averaging across the available half-hour bins, giving equal weight to each time of day within a site-month. We then calculated site-level standardized 30-min flux rates by averaging monthly means. This approach reduced bias from uneven temporal sampling, as heavily sampled hours or months did not dominate the site mean.

We calculated daily fluxes using a similar lookup-table-based gap-filling approach that preserved diel structure. For each site date, we created a complete half-hour grid and retained observed half-hour fluxes when available. We filled missing half-hour values hierarchically using the most temporally and site-specific available mean: site-month-hour, site-season-hour, site-biseason-hour, site-annual-hour, all site-month-hour, all site-season-hour, all site-biseason-hour, all site-annual-hour, all site-annual mean, and finally the global mean. Filled half-hour fluxes were summed to produce daily CH_4 fluxes in $mg\ C\ m^{-2}\ d^{-1}$. This approach uses the best available flux estimate to produce flux estimates less affected by sampling bias. Although sampling frequency is low at most sites, sufficient data in the site-month-half-hour bin dominated flux estimates (Supplementary Note 1).

Annual flux budgets were calculated by summing the gap-filled daily fluxes within each site-year and converting from milligrams to grams C. Site-level annual flux values were summarized as the mean annual budget across available years and reported in $\text{g C m}^{-2} \text{ yr}^{-1}$. We then used these annual categories as the common grouping variable for all final visual summaries, including the 30-min, daily, annual, diel, and map figures. Across all site-date half-hour slots used in the daily product, 15.0% were observed directly, 73.4% were filled from site-month-hour means, 8.5% from site-season-hour means, 2.2% from site-bi-season-hour means, 1% from site-annual-hour means, and 0.5% from site-annual-hour means (Supplementary Note 2).

In addition to scaled annual budgets, we also used a condition-based approach to develop annual budgets for each site. We included this condition-based approach to ensure that biases associated with conditions where observations were common do not affect the annual budgets. We gap-filled the 30-minute CH_4 data using a random forest (RF) approach driven by ERA5-Land reanalysis covariates¹²⁵. Hourly ERA5 data — 2-meter air temperature (T_{air}), soil moisture (SVWC; 0-7 cm and 7-28 cm), soil temperature (T_{soil}), precipitation, shortwave radiation (SWRAD), and vapor pressure deficit (VPD) — were obtained from the Open-Meteo Archive API for each NEON tower location and interpolated to 30-minute timestamps. Two RF models were then trained on the subset of observed 30-minute fluxes paired with ERA5 covariates: a site-level RF that included SITE_ID as a predictor to capture site-specific offsets, and a population-level RF without SITE_ID used for sites with fewer than 50 observed paired records. Both models used 500 trees, a minimum node size of 5, and a subsampling fraction of 0.70, implemented via the ranger package in R. Predictors included ERA5 climate variables, 7-day rolling means of temperature and precipitation, a temperature-soil moisture interaction term, site climatological CH_4 flux, harmonic hour-of-day terms, day of year, month, season, and ecosystem type. We applied the site-level RF to fill gaps at data-rich sites; elsewhere, we used the population-level RF. The population-level RF includes a site $\times$ time-of-day mean flux computed from each site's own observed record (falling back to season $\times$ hour, then hour, then global mean). This serves as an implicit site-level prior that encodes the sign and magnitude of a site's typical exchange pattern, so the model implicitly "knows" whether it's predicting for a sink or source context. Monthly mean CH_4 fluxes ($\text{g C m}^{-2} \text{ month}^{-1}$) were then aggregated from the ERA5-driven gap-filled half-hourly series. We assigned annual behavior categories based on the consistency of annual budget signs. We classified sites as weak sources when all annual fluxes were positive, weak sinks when annual fluxes were negative, and fluctuating otherwise. All analyses below used ERA5-gapfilled data.

In addition to the NEON tower sites, we used validation datasets from towers that measured both EC fluxes and simultaneous gradient mixing ratios of CH_4 that were also representative of upland ecosystems. We identified 3 validation towers: SE-Sto (2014-2017)¹²⁶, SE-Svb (2019)¹²⁷, and US-Uaf (2014-2019)¹²⁸. Both SE-Svb and SE-Sto were from the Integrated Carbon Observation System (ICOS), and US-Uaf was from the AmeriFlux network. Validation towers represented a subarctic peat plateau experiencing rapid permafrost degradation (SE-Sto), a boreal forest landscape in northern Sweden (SE-Svb), and a boreal forest on discontinuous permafrost in Alaska, USA (US-Uaf). Validation tower ecosystems had canopies ranging from <1 meter in the mire to ~3 meters in the black spruce forest of US-Uaf and 18-22 meters in the mixed coniferous

forest of SE-Svb, spanning the range of canopy heights at the NEON sites. As a result, tower heights ranged from 8 meters to 150 m. The tower SE-Svb is a tall tower equipped with EC instrumentation at an elevation of 85 m, capable of making landscape-scale EC flux measurements of gas exchange (with a flux footprint comprising ~90% forest and 10% mire). Validation towers were useful for understanding how gradient fluxes compare with EC fluxes (Supplementary Note 3). We used the same data processing to calculate gradient fluxes with the validation towers as was used for NEON data processing. We included the three validation towers to show that the gradient method can reproduce EC fluxes, and strong performance across ecosystem types for H₂O and CO₂ suggests we can derive reliable ecosystem exchange rates for CH₄⁶⁰.

We also incorporated fluxes from FLUXNET-CH₄⁴⁵, independent towers^{20–22,53,54,72–76} and chamber-based fluxes for upland ecosystems^{24–26,28,30,32–35,41,61–71}^{24–26,28,30,32–35,41,61–70}, and upland methane oxidation rates from the soil methanotrophy model MeMo³⁶. Literature values for towers, chambers, and models were included as benchmarks. While the literature included in this work focused on sentinel studies, we also searched for studies that reported rates for underrepresented ecosystem types to provide realistic ranges for upland fluxes. Comparisons were made at a moderate scale for daily flux rates, which were often reported by studies or could be determined without introducing substantial bias.

We ensured that F_{storage} and flux upscaling did not introduce systematic biases in the patterns observed across NEON sites (Supplementary Note 2). We ensured that the annual site budget and the weak-source or weak-sink class did not materially affect the conclusions (Supplementary Note 2-5). Storage was small and symmetric; lateral inputs did not affect classification; and gap-fill variance compression was symmetric and canceled out over annual integration (Supplementary Note 2).

Terrestrial Ecosystem Flux Upscaling

Monthly upland CH₄ flux observations were compiled from NEON ERA5-gapfilled fluxes. This upscaling included sites spanning forest, grassland, shrubland, and arid ecosystem types across North America. Half-hourly flux measurements (gap-filled CH₄ in mg C m⁻² 30 min⁻¹) were aggregated to monthly totals and joined to concurrent ERA5 climate variables: monthly mean 2m air temperature (Tair) and volumetric soil water content (VSWC). Long-term site attributes — mean annual precipitation (MAP, mm yr⁻¹) and mean annual temperature (MAT, °C) — were obtained from site metadata, and an aridity index was computed as MAP / (MAT + 10). Site-months with non-finite values were excluded, yielding 2,052 site-month observations. We labeled a site-month a net source if the monthly CH₄ budget exceeded zero.

We produced a spatial upscaling that estimates the net terrestrial sink using a two-stage random forest (RF) pipeline to upscale monthly CH₄ exchange to the ERA5 0.25° grid (2000-2025). Stage 1 predicted the probability that a grid cell in a given month acted as a net CH₄ source. Stage 2 predicted the flux magnitude separately for source and sink conditions using two independent regression forests. We derived three upscaling approaches from these models, differing only in

how P(source) was converted to a cell-level flux assignment, and evaluated them against the GMB upland soil sink estimate of -35 Tg CH₄ yr⁻¹ to diagnose scale-dependent bias.

In stage 1, the state-probability model was fitted using the *ranger* package (v0.16) in R, each with 500 trees, minimum node size of 20, maximum tree depth of 8, and a subsampling fraction of 0.70 without replacement (seed = 42). Predictors were ecosystem type (forest, grassland, shrubland, arid), monthly mean T_{air} (°C), monthly mean VSWC (m³ m⁻³), MAP (mm yr⁻¹), MAT (°C), and aridity index. We trained the model on a 1:1 downsampled subset (425 sinks + 425 sources) to eliminate class imbalance. We then calibrated OOB class probabilities by fitting isotonic regression of observed source/sink labels to OOB-predicted probabilities, yielding calibrated P(source) estimates used in both Stage 2 and spatial projection. We evaluated model skill against OOB predictions using the area under the receiver-operating-characteristic curve (AUC), Brier score and associated skill score, and Tjur R². We summarised classification performance at a 0.5 probability threshold in terms of accuracy, sensitivity, and specificity. Predictor importance was ranked by the permutation-based variable importance metric returned by *ranger*.

In the second stage, we fitted conditional flux magnitude models separately for weak-sink and weak-source months. This separation was necessary because uptake and emission mechanisms and magnitude distributions were asymmetric. Upland CH₄ uptake is constrained by diffusion, methanotrophic activity, and soil aeration, whereas weak upland emissions can occur under wetter microsites, pulses, or storage/transport conditions. Two magnitude forests were trained, one for sink conditions (Weak-sink) and one for source conditions (Weak-source). The response variable was log-transformed absolute monthly flux to stabilize variance. Predictors were standardized T_{air}, VSWC, MAP, and MAT (z-scores), stage 1 calibrated P(source), an aridity indicator (binary; aridity index < 15), and ecosystem type. Sink predictions were constrained to ≤ 0 and source predictions to ≥ 0. Log transformation reduced right skew and improved predictive accuracy for low-magnitude fluxes. Back-transformed fitted values were evaluated against observed magnitudes using Pearson r and RMSE (g C m⁻² month⁻¹).

The three upscaling approaches differed in how they applied the state probability model. Approaches included a dichotomous and a continuous application, with a dichotomous application using a threshold to generate the largest possible estimate of the net terrestrial sink. The dichotomous approach used a hard threshold at P(source) ≥ 0.50. Cells were assigned exclusively to either flux_{source} or flux_{sink}. The 0.50 threshold is Bayes-optimal for calibrated probabilities under symmetric misclassification costs. The continuous approach did not have a hard threshold; cells near the decision boundary received a probability-weighted blend of both flux components (Eq.10):

$$F_{CH_4} = P_A(\text{source}) \times \text{flux}_{\text{source}} + [1 - P_A(\text{source})] \times \text{flux}_{\text{sink}} \quad \text{Eq.10}$$

The continuous state was applied to preserve the magnitude and variability of methane exchange. This approach is ecologically faithful because F_{CH_4} responds continuously to soil moisture, redox conditions, temperature, plant transport, substrate availability, disturbance, and microbial community structure. Results will show whether systems are becoming weaker sinks, stronger sources, or more variable before they fully “flip” categories. In the GMB-Dichotomous expression, the probabilities were determined with a post-hoc threshold P^* selected so that the mean annual global budget was closest to the GMB upland soil sink estimate of $-35 \text{ Tg CH}_4 \text{ yr}^{-1}$. A varying the $P(\text{source})$ threshold from 0.30 to 0.99 at 0.01 increments was performed, and P^* was determined by linear interpolation ($P^* = 0.990$).

Global ecosystem classification was based on the MODIS MCD12C1⁷⁷ annual land-cover product, using the Level-1 biomes from the Ecoregions2017 dataset ¹²⁹. Forest biomes (biome codes 1-6) were assigned to forest; tropical and temperate grasslands, savannas, and flooded grasslands (codes 7-11) to grassland; Mediterranean and xeric shrublands (codes 12-13) to shrubland; and cells with an aridity index ($MAP / (MAT + 10) < 15$) to Arid. The aridity index was computed as $MAP / (MAT + 10)$ ¹³⁰, consistent with the UNEP drylands classification scheme ¹³¹. Arid cells were remapped to the Shrubland class for RF prediction but carried a binary ‘is_arid’ flag that forced their predicted $P(\text{source})$ to zero during spatial projection (see Section 2.3). The MAP (mm yr^{-1}) and MAT ($^{\circ}\text{C}$) were derived from ERA5-Land climatological averages (2000-2020). Monthly ERA5-Land 2-meter air temperature (T_{air} , $^{\circ}\text{C}$) and volumetric soil water content (VSWC, $\text{m}^3 \text{ m}^{-3}$) provided inter-annually varying drivers for spatial projection. We standardized them to z-scores using their respective training-set means and standard deviations. Inundation fraction for each cell was taken from the Water Bodies and Dynamic Wetlands (WAD2M) dataset ⁷⁸, and the upland area fraction ($1 - \text{inundation fraction}$) was applied when computing cell-level CH_4 budgets, thereby excluding standing-water area from terrestrial flux integration.

Monthly predictions were generated for all upland ERA5 0.25° grid cells over 2000-2025 using ERA5-Land climate forcing, MODIS MCD12C1 annual land cover, and WAD2M inundation fractions. Arid cells (aridity index < 15) were assigned $P(\text{source}) = 0$ to prevent extrapolation and ensure the sink magnitude model was applied. This choice was conservative to address the poor representation of NEON arid sites relative to global conditions. This was necessary to prevent high temperatures from dominating the $P(\text{source})$ prediction in an unlikely direction. We converted annual cell fluxes from $\text{g C m}^{-2} \text{ yr}^{-1}$ to $\text{Tg CH}_4 \text{ yr}^{-1}$ using upland cell area and summed them globally. The WAD2M was available from 2000 to 2020, so the 5 most recent years (2021-2025) use climatological inundation fractions rather than observed values, which are the mean monthly inundation fractions (2000-2020). We explored the sensitivity of the global upland terrestrial CH_4 budget to bias in gradient flux magnitude (Supplementary Note 5-6).

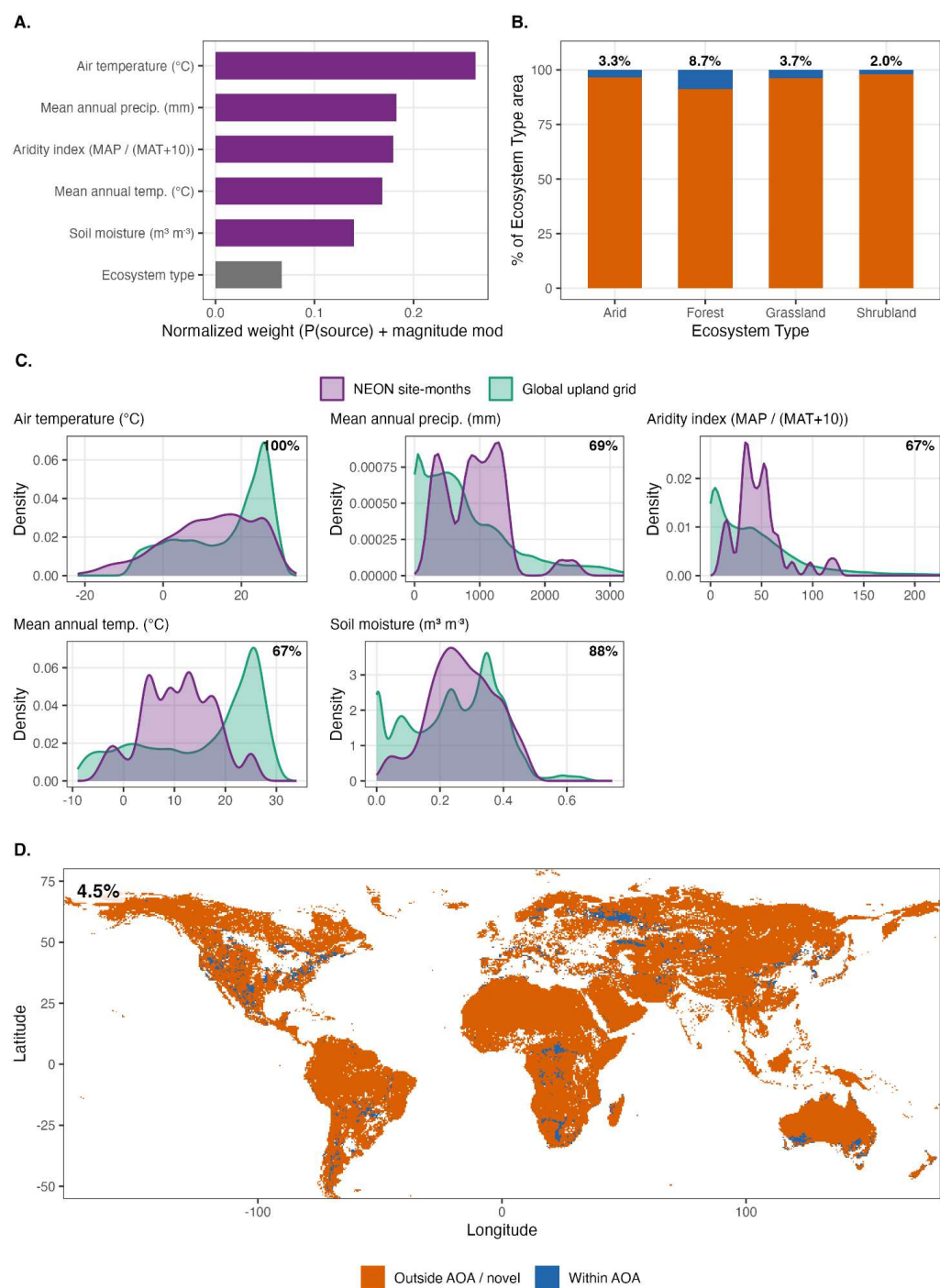
NEON Site Representativeness

We conducted an Area-of-Applicability (AOA)/Dissimilarity Index (DI) analysis ¹³² to evaluate the representativeness of NEON tower sites for global terrestrial upland ecosystems. This approach combined the RF variable importances from the Stage 1 $P(\text{source})$ model and the Stage 2

832 magnitude models into a single weight per shared predictor (air temp, soil moisture, MAP, MAT,
833 AI). We built an importance-weighted standardized distance space and, within each ecosystem
834 type NEON sampled, stratified to compute how far each global upland grid cell was from its
835 nearest NEON site-month, relative to how far NEON sites typically were from each other.
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838 **Extended Data Figures/Tables**



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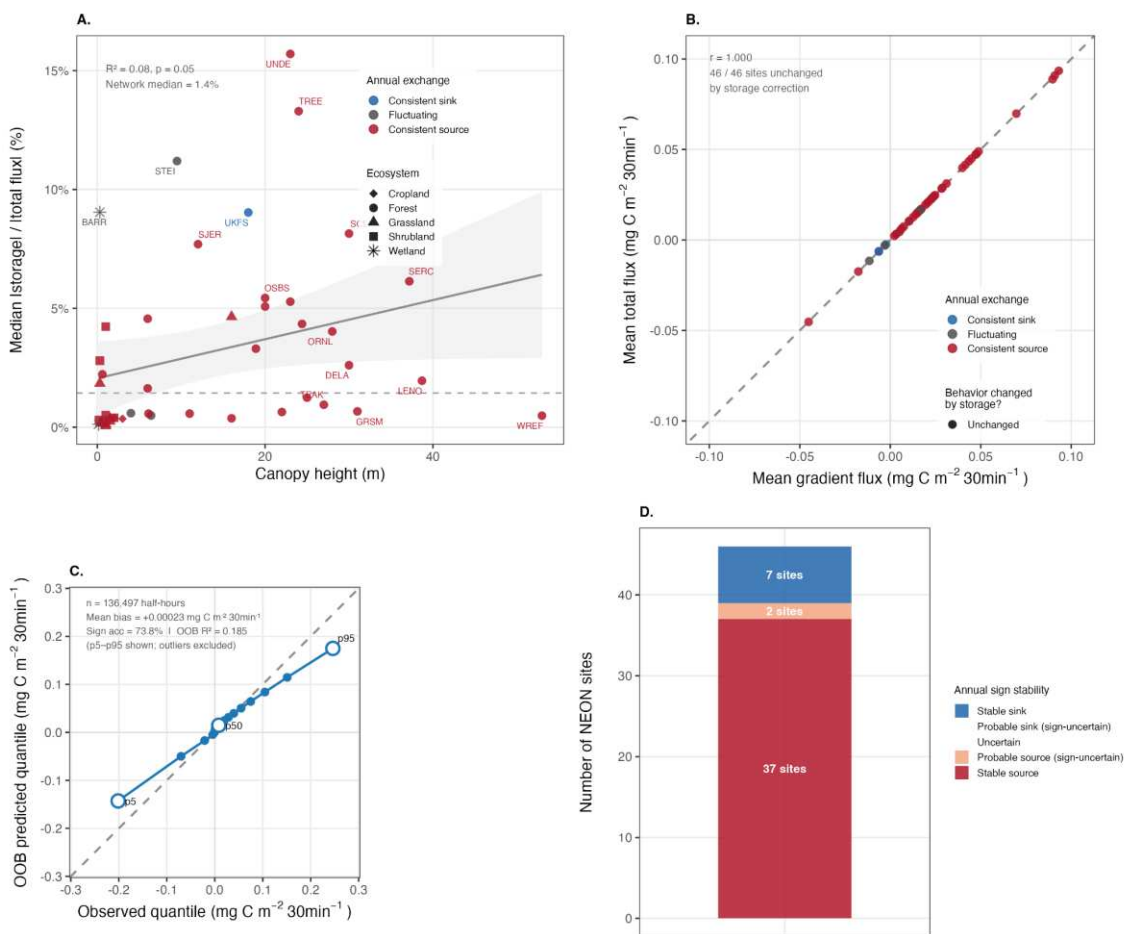
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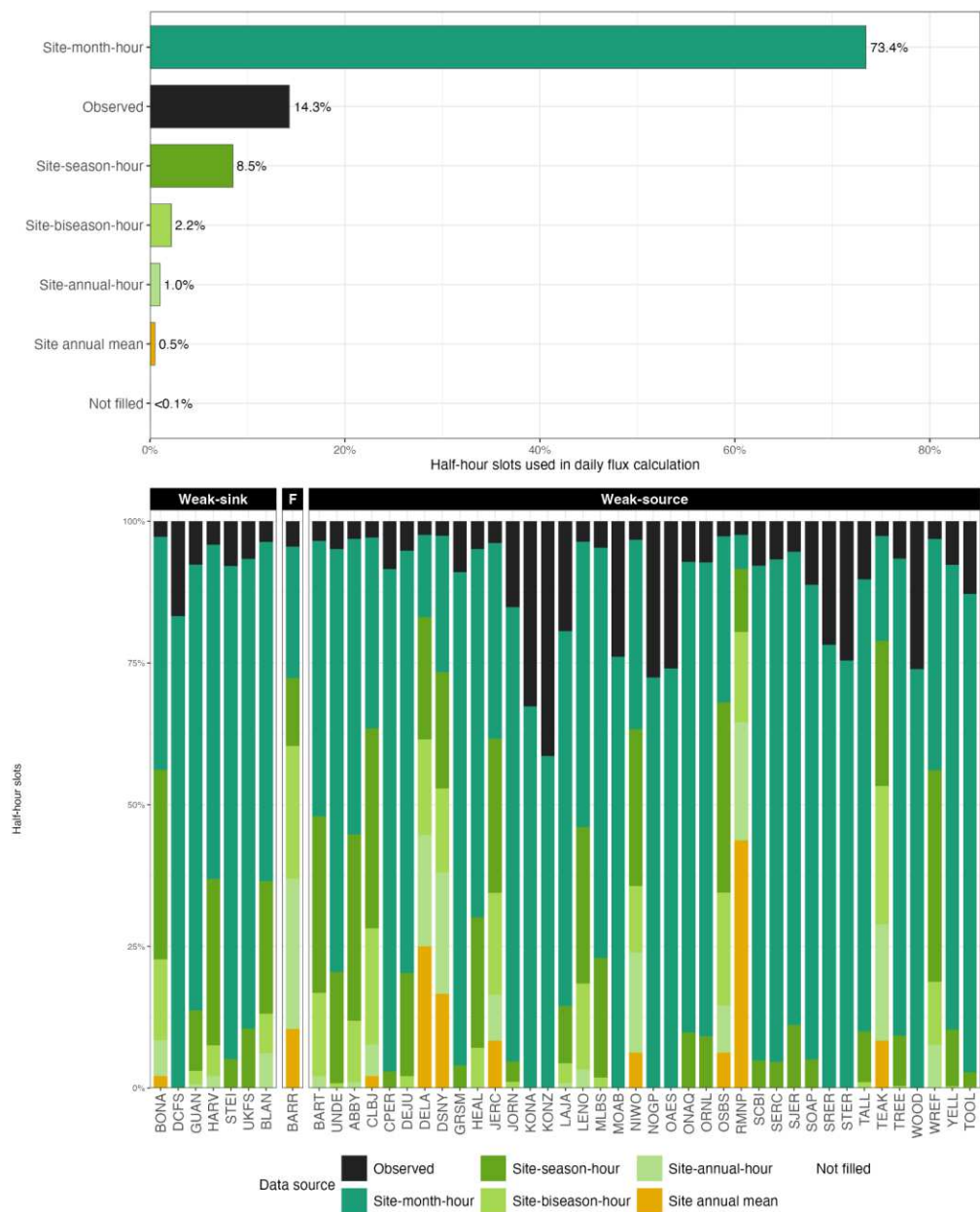
Extended Data Fig. 1. Climatic and ecological representativeness of NEON training data relative to the global upland CH₄ upscaling domain, based on a dissimilarity-index (DI) Area-of-Applicability (AOA) analysis for the representative year (2025). (A) Combined variable-

importance weights, pooled across the Stage 1 P(source) and Stage 2 magnitude models, were used to construct the multivariate distance metric underlying the AOA classification. (B) Area-weighted representativeness by ecosystem type. (C) Predictor coverage: density distributions of each continuous covariate for NEON training data versus the global upland grid (area-weighted). Labels show the percentage of global upland area that falls within NEON's observed range for each variable: air temperature, soil moisture, mean annual precipitation, aridity index, and mean annual temperature. (D) Global map of AOA classification across upland grid cells. Despite the high single-variable coverage shown in (C), only 4.5% of global upland area was within NEON's joint, multivariate AOA.

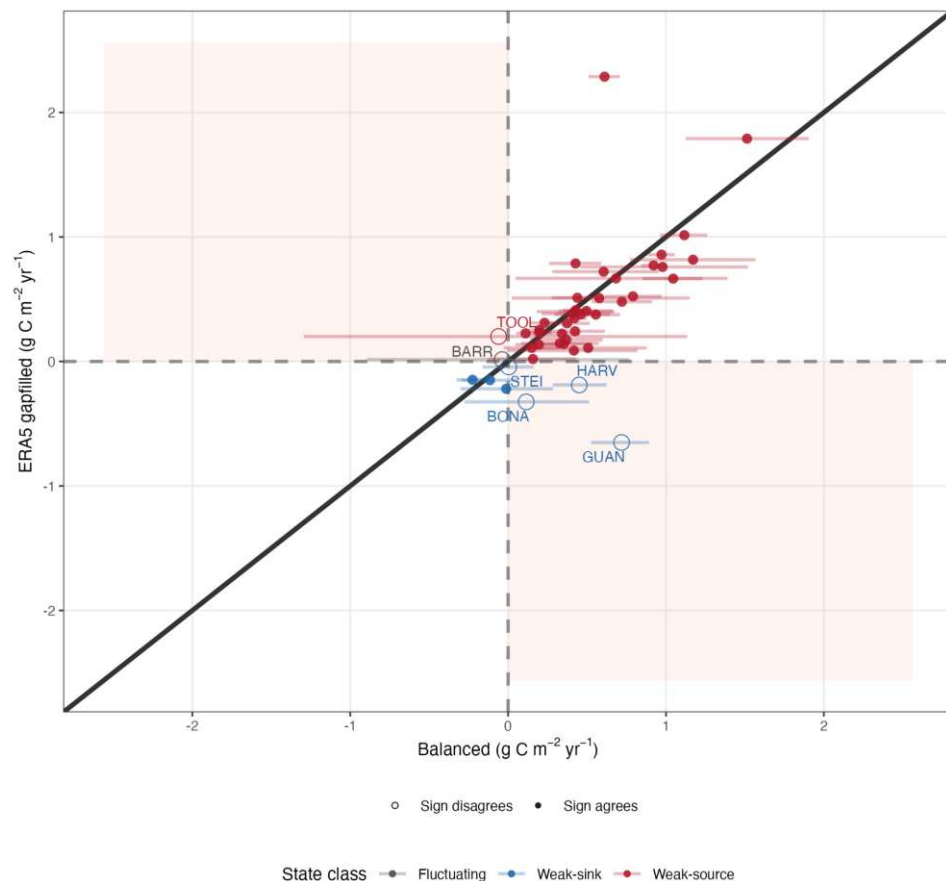


Extended Data Fig. 2. Justification of the flux-gradient methodology. (A) Median within-canopy storage fraction vs. canopy height; the relationship is weak and does not reach conventional significance ($R^2 = 0.08$, $p = 0.05$). (B) Site-mean total flux (gradient + storage term) vs. gradient-only flux: all points lie on the 1:1 line, and no site changes exchange class when the storage correction is added or removed. (C) OOB quantile-quantile plot (p5-p95) of ERA5-RF predicted vs. observed 30-minute CH_4 flux for 136,497 training half-hours; the S-shaped deviation reflects

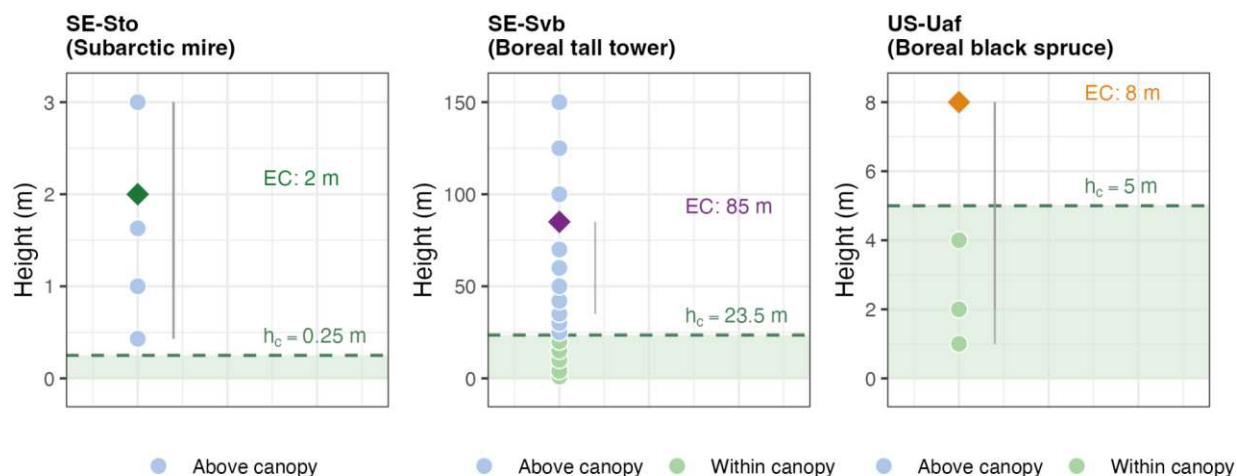
860 symmetric variance compression, with near-zero mean bias ($+0.000225 \text{ mg C m}^{-2} 30 \text{ min}^{-1}$). (D)
861 Annual budget sign stability under gap-fill uncertainty.



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863 **Extended Data Fig. 3.** The frequency of data sources used for daily CH₄ gap-filling. We
864 summarized gradient fluxes (30-min, daily, and annual) in a balanced site-month-hour
865 framework.



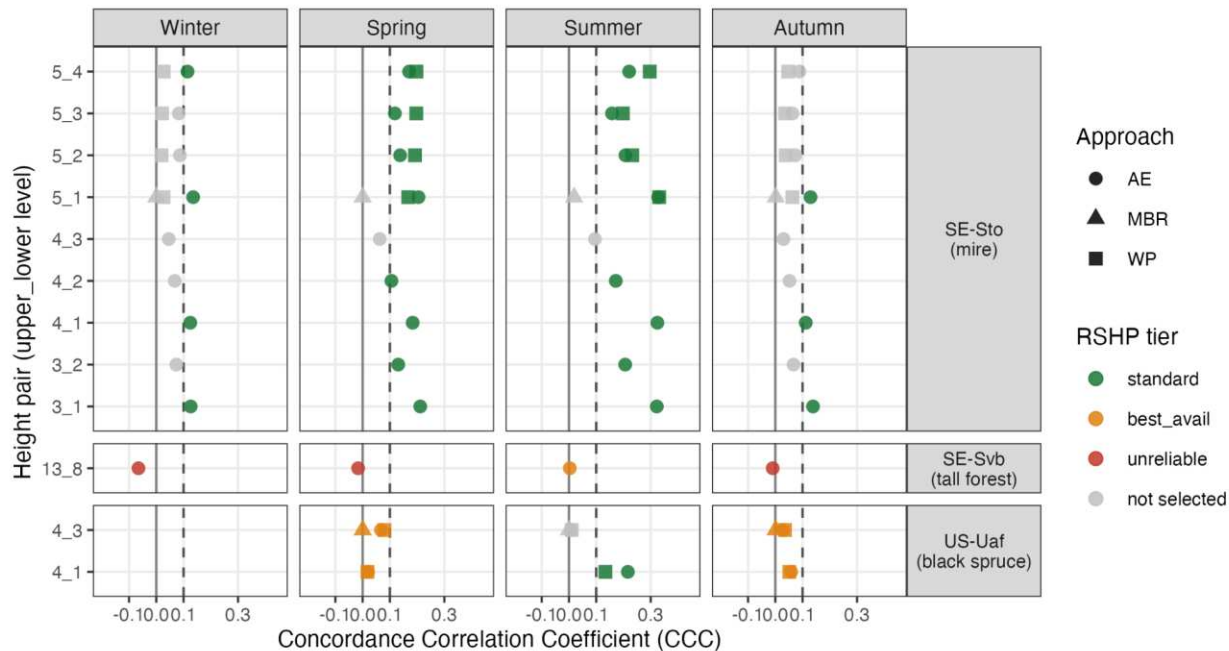
Extended Data Fig. 4. Observed versus predicted for standardized annual budgets and ERA-5 gap-filled annual budgets for NEON tower sites.



Extended Data Fig. 5. Measurement height configurations at validation towers. We used the upper height to understand when measurement levels should be considered within the canopy.

Extended Data Table 1. Structural characteristics of validation towers. We defined canopy height (h_c) as the tallest height reported for each footprint.

Site	Ecosystem	Top Canopy Height (h_c ; m)	Tower (m)	Measurement levels	CH ₄ levels with data	EC height (m)	IGBP
SE-Sto ^{126,134}	Subarctic peat mire	0.25	3.07	5 (0.43-3.0 m)	5 (all)	2.0	WET
SE-Svb ¹²⁷	Boreal mixed conifer	23.5	150	16 (1-150 m)	2 (35, 85 m)	85	ENF
US-Uaf ¹²⁸	Boreal black spruce	5.0	8	4 (1-8 m)	3 (1, 4, 8 m)	8	ENF

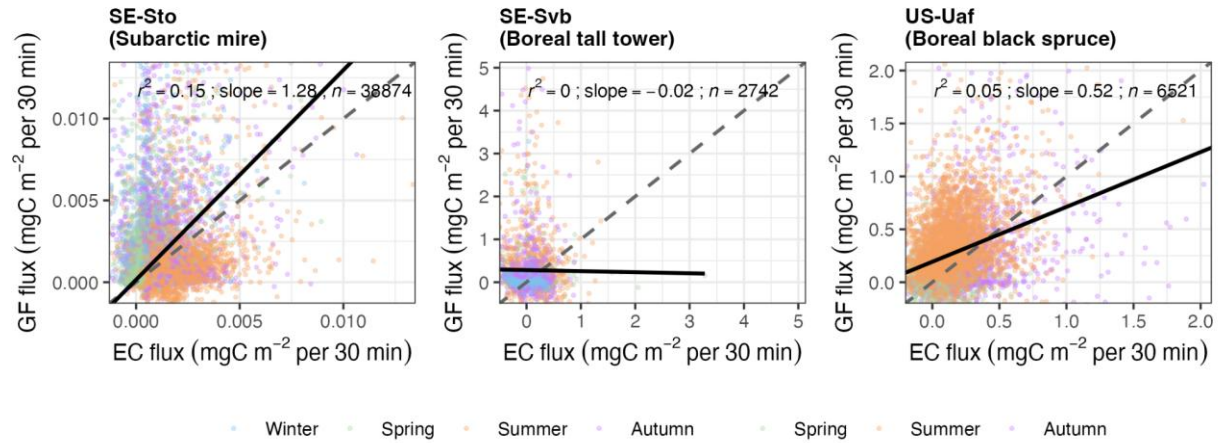


Extended Data Fig. 6. Concordance correlation coefficients (CCC) for candidate RSHP height pairs by season and approach.

Extended Data Table 2. Representative sampling height pairs (RSHP) selected per site-season-approach (highest CCC within tier shown).

Site	Season	Approach	Height pair	CCC	RSHP tier
SE-Sto	Winter	AE	5_1 (3.0-0.43 m)	0.135	standard
SE-Sto	Spring	AE	3_1 (1.63-0.43 m)	0.211	standard
SE-Sto	Summer	AE	5_1 (3.0-0.43 m)	0.327	standard

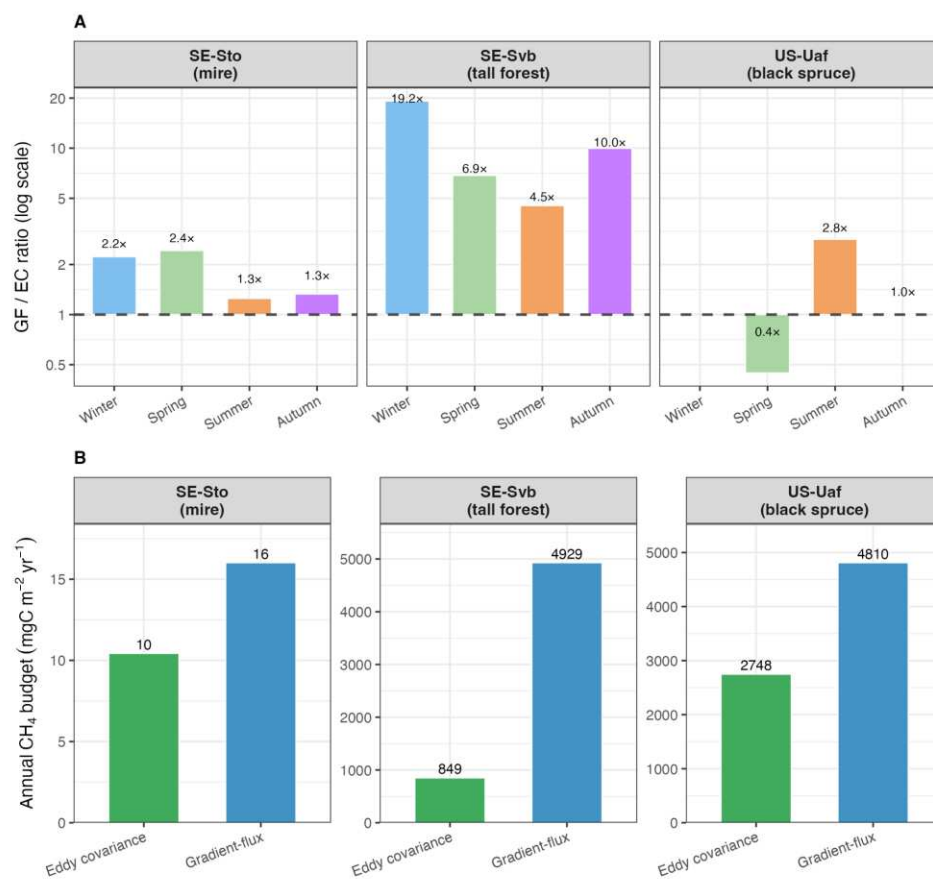
SE-Sto	Summer	WP	5_1 (3.0-0.43 m)	0.331	standard
SE-Sto	Autumn	AE	3_1 (1.63-0.43 m)	0.138	standard
SE-Svb	Summer	AE	13_8 (85-35 m)	0.003	best_avail
SE-Svb	Winter	AE	13_8 (85-35 m)	-0.065	unreliable
US-Uaf	Summer	AE	4_1 (8-1 m)	0.216	standard
US-Uaf	Summer	WP	4_1 (8-1 m)	0.134	standard
US-Uaf	Spring	WP	4_3 (8-4 m)	0.080	best_avail
US-Uaf	Autumn	AE	4_1 (8-1 m)	0.058	best_avail



Extended Data Fig. 7. Half-hourly GF vs EC CH_4 fluxes at each validation site.

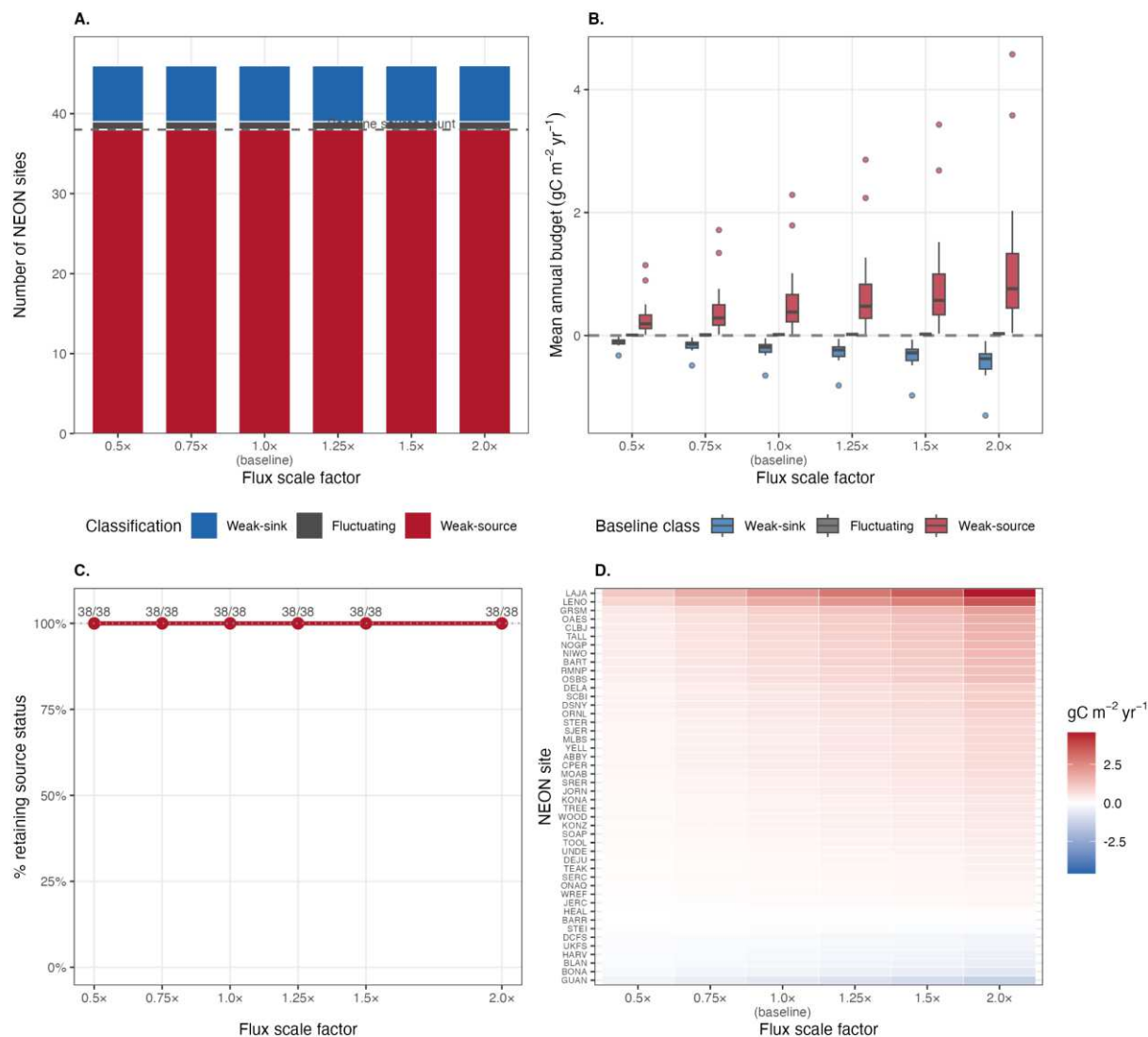
Extended Data Table 3. The 30-minute GF vs EC performance and pseudo-annual CH_4 budget comparison. Annual values are not gap-filled (sampled periods only).

Site	n (30-min)	r	Slope	GF annual (mg C m ⁻² yr ⁻¹)	EC annual (mg C m ⁻² yr ⁻¹)	GF/EC
SE-Sto	38,874	0.385	1.28	16.1	10.4	1.54
SE-Svb	2,742	-0.005	-0.025	4,929	850	5.80
US-Uaf	6,521	0.228	0.52	4,810	2,748	1.75

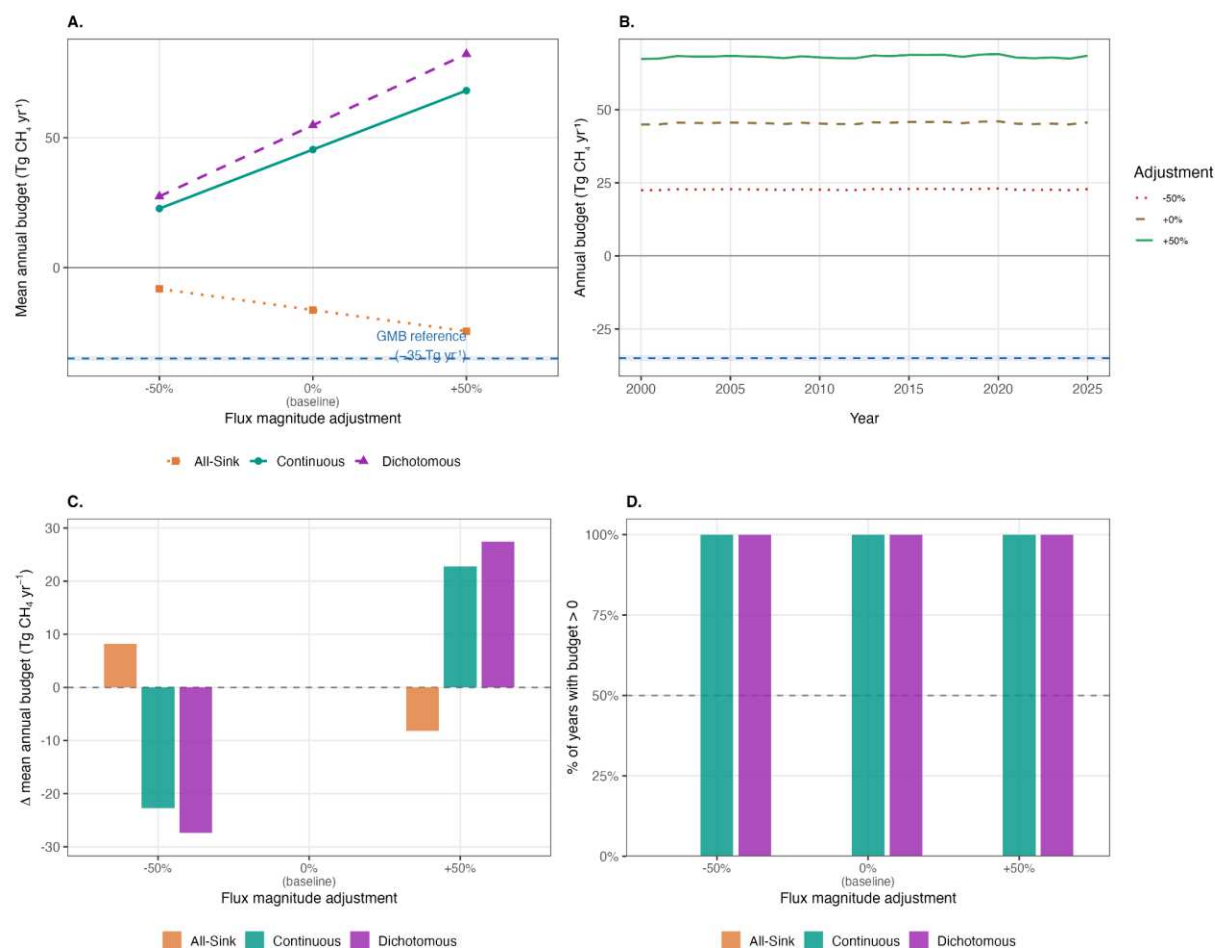


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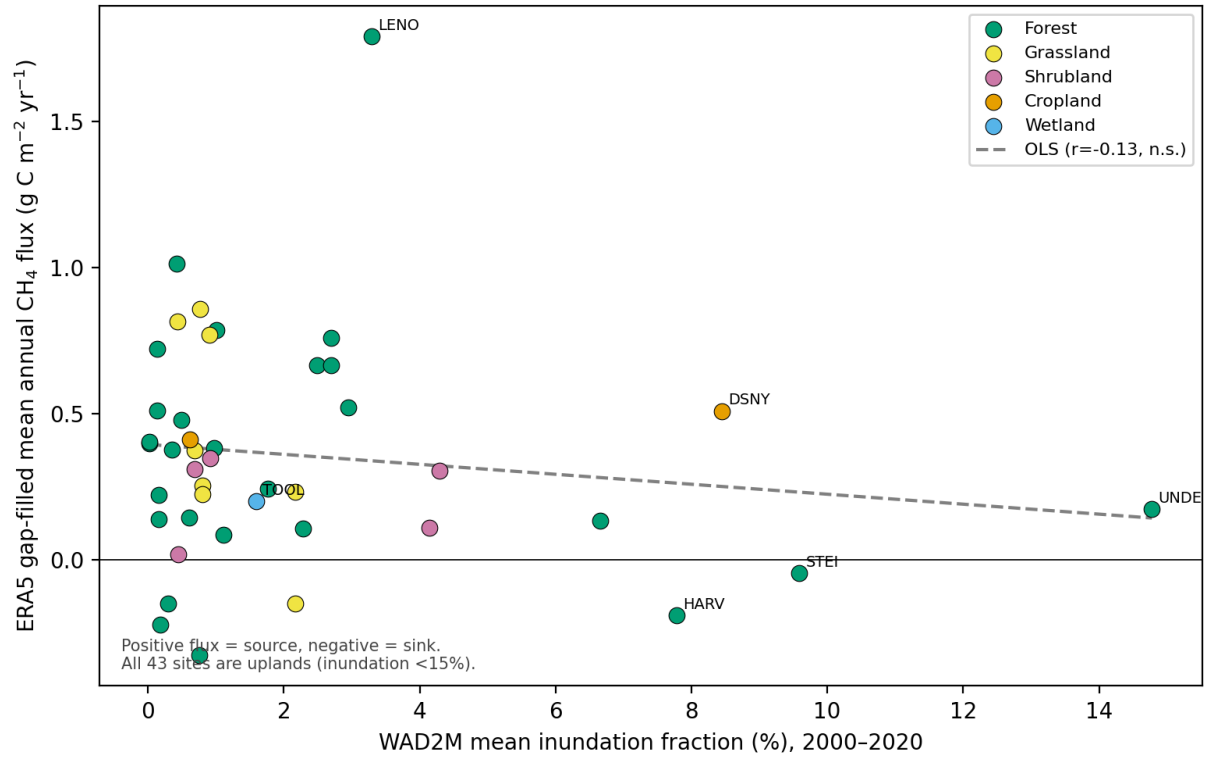
888 **Extended Data Fig. 8. Seasonal GF/EC ratio and scaled-annual budget comparison.**



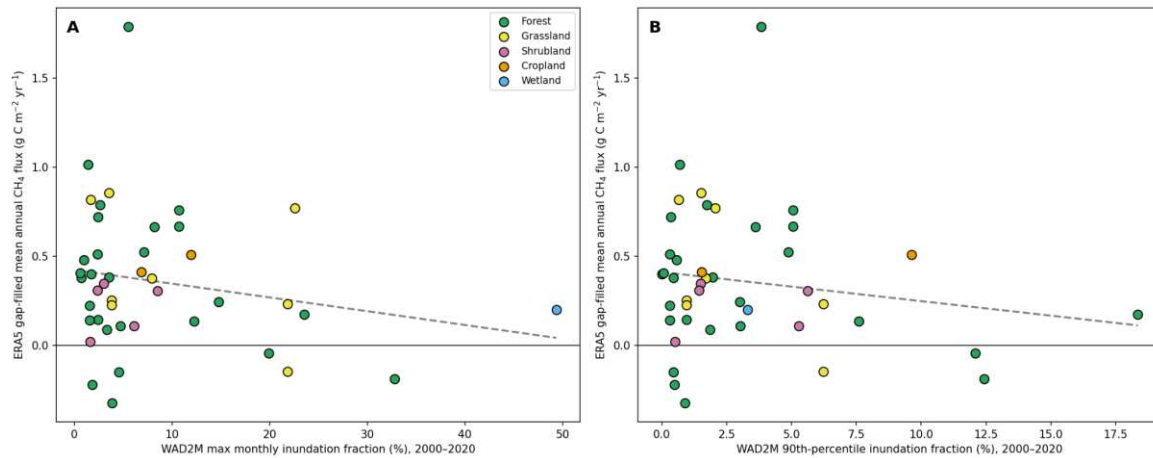
889 **Extended Data Fig. 9.** Sensitivity of NEON network CH_4 source/sink classification to systematic
890 scaling of gap-filled flux magnitudes. (A) Number of NEON sites classified as Weak-source,
891 Fluctuating, or Weak-sink at each scaling level; dashed line marks the baseline (1.0x) source
892 count. (B) Distribution of mean annual CH_4 budgets across sites at each scaling level; box fill
893 indicates baseline classification; dashed line marks zero. (C) Percentage of baseline Weak-
894 source sites retaining their source classification at each scaling level; labels show the count of
895 sites retaining source status out of all baseline sources. (D) Per-site mean annual CH_4 budget
896 ($\text{g C m}^{-2} \text{yr}^{-1}$) at each scaling level, ordered by baseline budget magnitude; blue indicates net
897 sink, red indicates net source. Results demonstrate that the continental-scale source signal is
898 robust to flux-magnitude uncertainty of at least a factor of two.



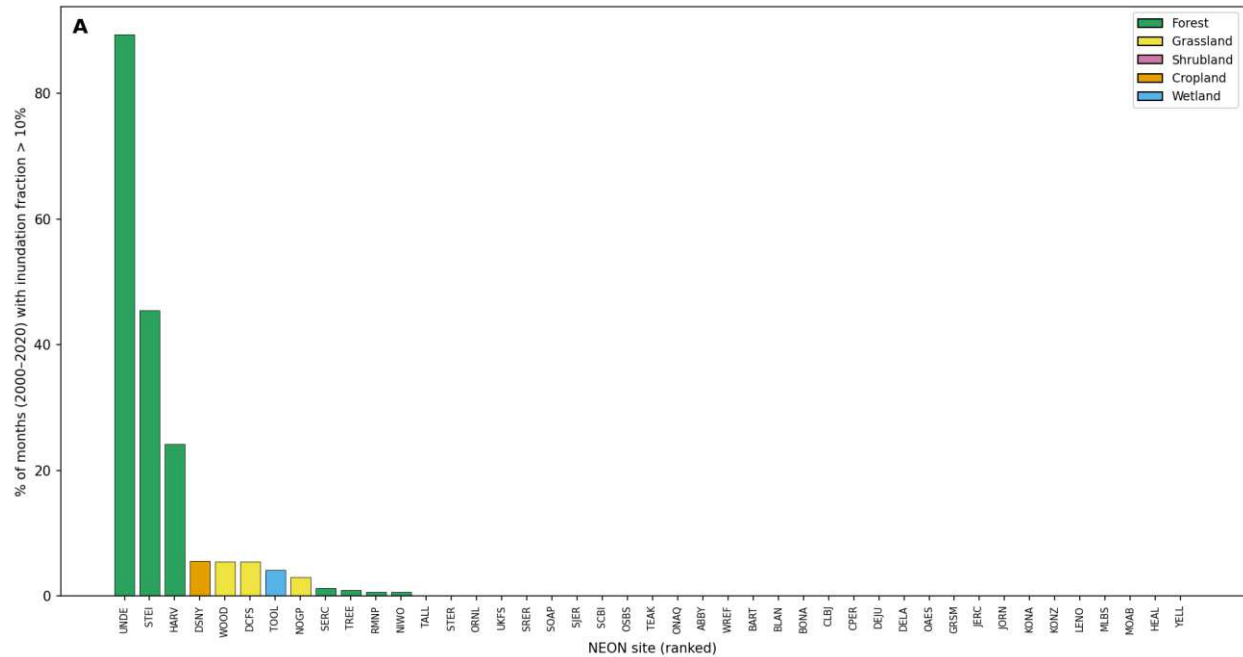
Extended Data Fig. 10. (A) Mean annual budget ($\text{Tg CH}_4 \text{ yr}^{-1}$) across scenarios for three modeling approaches (Continuous, Dichotomous, and All-Sink). The shaded column marks the scenario corresponding to the observed validation bias, and the blue band shows the GMB upland soil sink reference ($-35 \text{ Tg CH}_4 \text{ yr}^{-1}$) for context. (B) Annual time series of the Continuous-approach budget at baseline and key bias scenarios. (C) Absolute change in mean annual budget relative to the 0% baseline scenario for each approach. (D) Percentage of years (2000-2025) in which the adjusted budget remains net positive (source) under each scenario.



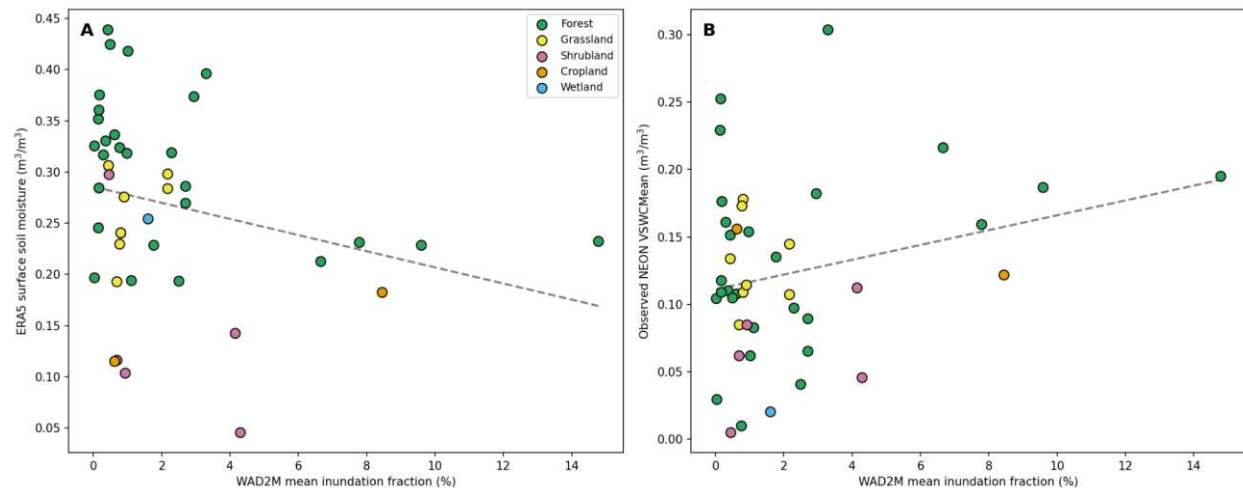
Extended Data Fig. 11. Mean WAD2M inundated fraction (2000–2020) versus ERA5 gap-filled mean annual CH_4 flux at the 43 NEON gradient-flux sites with WAD2M coverage. Points colored by ecotype; dashed line is the OLS fit. The relationship is flat and non-significant.



Extended Data Fig. 12. (A) The maximum (left) and (B) 90th-percentile monthly inundated fraction versus annual CH_4 flux. Peak wetness does not shift sites toward emission; both relationships are negative and non-significant. Labeled points are the wettest sites.



Extended Data Fig. 13. Percentage of months (2000–2020) in which each site's cell exceeded 10% inundated area, ranked. Only UNDE, STEI, and HARV show appreciable inundation frequency; most sites are effectively never inundated.



Extended Data Fig. 14. Soil water content versus WAD2M inundated fraction. Left: ERA5 modeled surface soil moisture. Right: observed NEON volumetric soil water content. Grid-scale inundation does not track in situ wetness within the tower footprint.

Extended Data Table 4. lists the ten sites with the highest peak inundation. It provides a transparent watch-list: these are the only sites where transient wetness could plausibly affect upland representativeness, yet their CH_4 fluxes remain small and are not systematically positive.

Site	Ecotype	CH ₄ class	Mean Fw (%)	p90 Fw (%)	Max Fw (%)	% mo. >10%	Flux (gC m ⁻² yr ⁻¹)
TOOL	Wetland	Weak-source	1.6	3.3	49.3	4	0.20
HARV	Forest	Weak-sink	7.8	12.4	32.8	24	-0.19
UNDE	Forest	Weak-source	14.8	18.3	23.5	89	0.17
NOGP	Grassland	Weak-source	0.9	2.1	22.6	3	0.77
DCFS	Grassland	Weak-sink	2.2	6.2	21.8	5	-0.15
WOOD	Grassland	Weak-source	2.2	6.2	21.8	5	0.23
STEI	Forest	Weak-sink	9.6	12.1	19.9	45	-0.04
TREE	Forest	Weak-source	1.8	3.0	14.8	1	0.24
SERC	Forest	Weak-source	6.7	7.6	12.3	1	0.14
DSNY	Cropland	Weak-source	8.4	9.6	11.9	6	0.51

Data Availability

The multi-site gradient-flux benchmark dataset is publicly archived via EDI. Files include EC and GF fluxes by method and sampling height pair, along with corresponding micrometeorological data. Site-level canopy complexity from NEON AOP and metadata for tower geometry and sensor heights. The archive adheres to FAIR data principles by providing findable, DOI-based access, interoperable formats, reusable metadata, and transparent version control. Versioned DOI will be provided upon acceptance. Future releases may incorporate CH₄, additional NEON years, and additional benchmark methods. Data download and flux calculation code is written in R and archived on GitHub: <https://github.com/lter/lterwg-flux-gradient>. All filtering, ensemble, and analysis code is also written in R and archived on GitHub: <https://github.com/lter/lterwg-flux-gradient-methane>. *Both repositories will be published on Zenodo upon acceptance.

Author Contribution

SLM, JM, CRS, KD, CF, CS, DR, SJ, RC, JG, and AD contributed to the project's conceptualization and investigation through participation in the invited workshop and monthly meetings. SLM provided project administration and supervision. CRS led the flux calculations. SLM, SJ, JM, KD, JG, CS, AC, and CRS performed the data analysis and project execution. CS, CF, JC, HI, EL, IM, MP, MU, AM, JH, and ML provided resources and data curation,

contributing critical site-specific data and expertise to the synthesis. All authors contributed to the review and editing of the manuscript.

Competing Interest declaration

Authors have no competing interests to declare.

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