

# TundraFlux: A database of ecosystem respiration with biotic and abiotic metadata from Arctic and alpine tundra warming experiments

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## Abstract

Empirical *in-situ* measurements of ecosystem carbon dioxide respiration ( $R_{eco}$ ) in high-latitude ecosystems remain limited, yet they are essential for understanding how tundra carbon cycling responds to climate warming across different environmental contexts and for reducing uncertainties in upscaled carbon budgets and carbon–climate feedbacks. Here, we present the TundraFlux Database, which to date is the most comprehensive synthesis of tundra  $R_{eco}$  responses to experimental warming. The database compiles over 24,000 daily-aggregated *in-situ*  $R_{eco}$  measurements from control and warmed plots with open-top chambers at 64 Arctic and alpine tundra sites across 12 countries. By coupling  $R_{eco}$  measurements with extensive metadata on climate, vegetation, and soil characteristics, the TundraFlux Database enables the integration of field-scale ecological processes into large-scale models, offering new opportunities to refine global carbon budgets and test predictions of tundra ecosystem responses to warming. Open access to the TundraFlux Database will empower the research community to better quantify and predict how warming alters carbon cycling in Arctic and alpine tundra ecosystems. The data can be accessed on Zenodo (DOI: [10.5281/zenodo.17976235](https://doi.org/10.5281/zenodo.17976235), Schwieger et al., 2026).

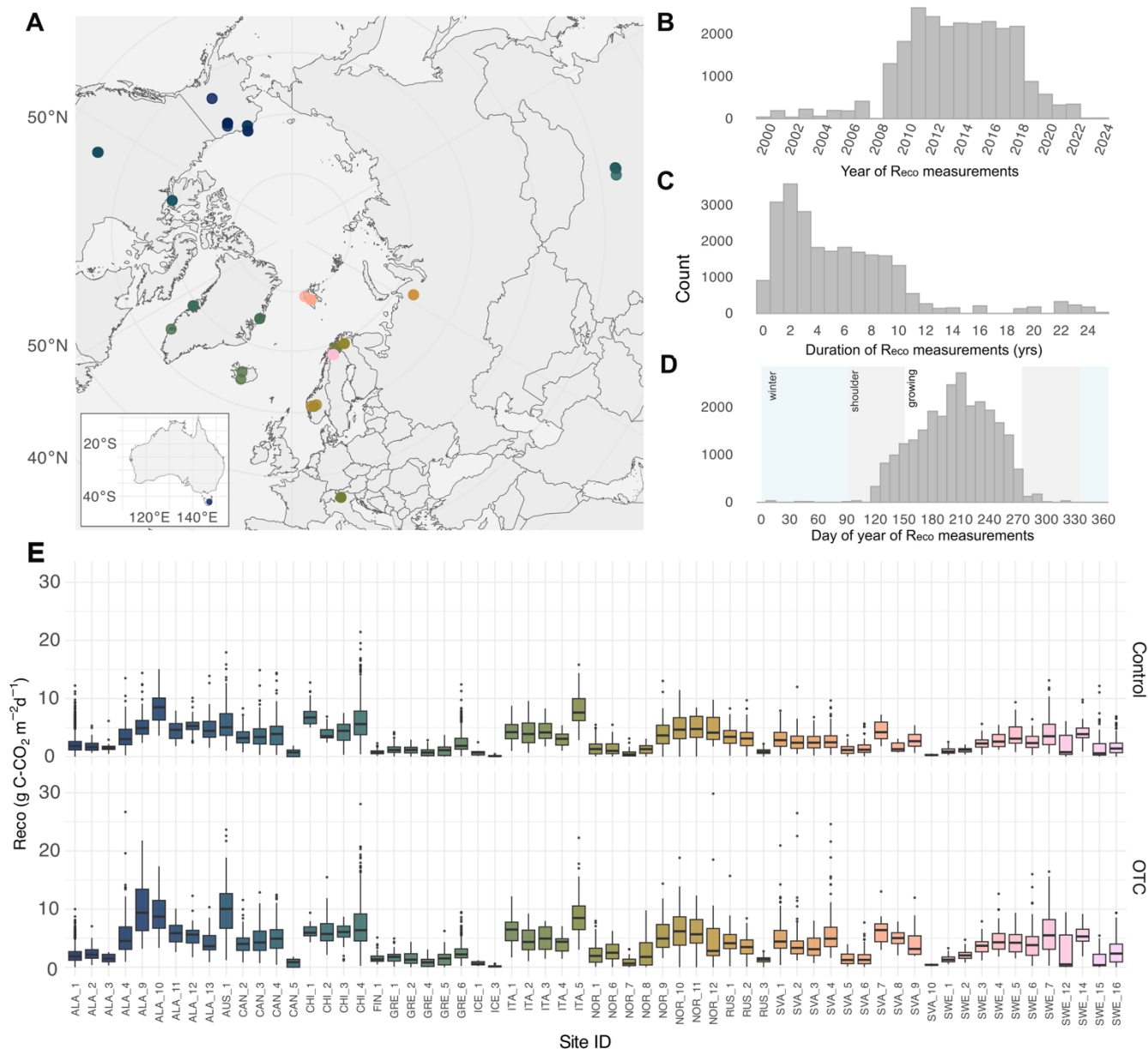
**Keywords:** Arctic tundra, alpine tundra, ecosystem respiration, open-top chambers (OTCs), warming experiments, database, carbon dioxide flux, vegetation data, soil data, climate data

## 1 Introduction

Ecosystem carbon dioxide ( $CO_2$ ) respiration, the sum of autotrophic respiration from plants and heterotrophic respiration from soil organisms (i.e., fauna and microbes), constitutes the largest natural carbon flux from terrestrial ecosystems to the atmosphere (Jones et al., 1999; Lu et al., 2013; Oberbauer et al., 1998; Schuur et al., 2008; Tarnocai et al., 2009). The Arctic and alpine tundra biome stores one-third of global soil organic carbon, which is nearly twice the atmospheric carbon pool (Schuur et al., 2015), much of it locked in permafrost (i.e., soil that remains consecutively frozen for at least 2 years), organic-rich mineral soils, and peat (Gorham, 1991; Hugelius et al., 2020; Park et al., 2025; Schuur et al., 2022; Tarnocai et al., 2009; Zimov et al., 2006). As ecosystem  $CO_2$  respiration ( $R_{eco}$ ) is a temperature-sensitive process (Davidson et al., 2006; Gudas et al., 2021; Mahecha et al., 2010; Niu et al., 2024), understanding the consequences of the current rapid warming in Arctic and alpine tundra (Rantanen et al., 2022; Tingley and Huybers, 2013; Welker et al., 1999) is crucial for understanding climate-driven shifts in soil processes and global carbon cycling. Rising air and soil temperatures are expected to thaw permafrost, release previously stored soil organic carbon, and accelerate microbial decomposition of soil organic matter, thereby increasing  $CO_2$  emissions to the atmosphere (Dorrepaal et al., 2009; Friggens et al., 2025; Karhu et al., 2014; Maes et al., 2024; Rustad et al., 2001; Schimel et al., 2004, 2006), which could significantly amplify global climate change (Cox et al., 2000; Welker et al., 2004).

130 Ecosystem respiration plays a central role in the global carbon cycle, making it essential to predict how  $R_{eco}$  responds to climate change. However, accurately forecasting the extent, as well as the spatial and temporal variability of these responses, remains a major scientific challenge (Karhu et al., 2014; Maes et al., 2024; Rustad et al., 2001; Schuur et al., 2022; Sulman et al., 2018; Virkkala et al., 2021). Spatially, addressing these challenges requires moving beyond isolated case studies toward synthesizing empirical data across diverse tundra sites and microclimates. Temporally, interannual variability is high and data from the non-  
135 growing season are sparse, even though respiration during this period can contribute substantially to annual carbon budgets (Fahnestock et al., 1998, 1999; Natali et al., 2019; Welker et al., 2000). Here, we present the TundraFlux Database, which compiles  $R_{eco}$  measurements derived from open-top chamber (OTC) warming experiments. These experiments use small greenhouses to passively increase air temperatures during the snow-free season while allowing relatively free entry of precipitation (Hollister et al., 2023; Marion et al., 1997; Welker et al., 1997). They are commonly used to simulate climate  
140 warming at a plot-scale in low-stature Arctic and alpine tundra systems, e.g., in the International Tundra Experiment network (ITEX; <https://www.gvsu.edu/itex/>; Henry and Molau, 1997; Hollister et al., 2023). These experiments provide a unique opportunity to analyse patterns and drivers of  $CO_2$  respiration under warming conditions across bioclimatic gradients, which arise from differences in climate, vegetation, and soil characteristics (Maes et al., 2024). Experimental warming studies uniquely integrate multiple, interacting ecosystem responses, including vegetation dynamics, microbial activity, soil processes,  
145 and snow-mediated microclimate effects (Hollister et al., 2023; Leffler et al., 2016; Welker et al., 1997, 1999), all of which jointly regulate  $R_{eco}$  (Niu et al., 2024).

The TundraFlux Database currently includes 24,951  $R_{eco}$  observations, aggregated to daily values (whenever multiple measurements were made within the same day) from experimentally warmed and associated control plots across 64 Arctic and alpine tundra sites (Fig. 1A), with measurements conducted between 2000 and 2024 (Fig. 1B). Here, we describe the data  
150 sources, the database structure and variables (Sect. 2), as well as potential applications (Sect. 3), data coverage and resolution (Sect. 4), future directions (Sect. 5), and availability (Sect. 6) of the TundraFlux Database.



**Figure 1** A. Map showing the locations of the 64 open-top chamber experiments from which the ecosystem CO<sub>2</sub> respiration ( $R_{eco}$ ) measurements in the TundraFlux Database were derived. Temporal spread of the data showing **B.** the distribution of the year of  $R_{eco}$  measurements, **C.** the duration of  $R_{eco}$  measurements (start of flux measurements - start of the experiment), and **D.** the distribution of day-of-year for  $R_{eco}$  measurements, with shaded regions highlighting winter (Dec–Mar, light blue), shoulder (Oct–Nov, Apr–May, grey), and growing (Jun–Sep, white) seasons. **E.** Boxplots showing the daily average  $R_{eco}$  ( $\text{g C-CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) for each site, for both the unmanipulated control (i.e., ambient conditions, **top**) and the warmed treatment with open-top chambers (OTC, **bottom**). Boxes show the median and interquartile range (IQR, 25th–75th percentiles); whiskers extend to  $1.5 \times \text{IQR}$ , and values beyond the whiskers are plotted as outliers. Colours for Site ID are the same for all panels. The database includes occasional negative and exact-zero  $R_{eco}$  values. Negative values can result from instrument noise or brief net CO<sub>2</sub> uptake, while exact zeros may reflect contributor preprocessing (e.g., rounding or thresholding small fluxes).

## 2 Description and structure

### 2.1 Scope and purpose

165 Warming alters tundra ecosystems through a suite of interacting biotic and abiotic pathways, including changes in vegetation composition (Bjorkman et al., 2020; Collins et al., 2021; García Criado et al., 2025; Wilson and Nilsson, 2009), plant productivity (Hollesen et al., 2015; Myers-Smith et al., 2019), microbial activity (Frossard et al., 2021), decomposition rates (Sarneck et al., 2020; Schwieger et al., 2025), nutrient cycling (Weedon et al., 2012), growing season length (Barichivich et al., 2013; Collins et al., 2021; Myers-Smith et al., 2019; Oberbauer et al., 1998), and snow-mediated microclimate conditions  
170 (Morgner et al., 2010; Pattison and Welker, 2014; Rixen et al., 2022), as well as increased thermokarst activity and permafrost degradation, which can strongly alter soil structure and carbon availability and thereby contribute to ecosystem respiration ( $R_{eco}$ ) (Abbott and Jones, 2015; Lewkowicz and Way, 2019; Olefeldt et al., 2016; Vogel et al., 2009). These processes jointly regulate  $R_{eco}$ , making it an integrative indicator of tundra ecosystem responses to climate warming.

As these responses occur at multiple spatial and temporal scales and are significantly influenced by the local environmental  
175 context, a robust evaluation of the effects of warming on  $R_{eco}$  requires long-term, spatially diverse datasets that link flux measurements with detailed site and plot-level metadata. The TundraFlux Database was developed to address this issue, systematically compiling chamber-derived  $R_{eco}$  measurements from experimental warming studies in Arctic and alpine tundra ecosystems. Fin these efforts by specifically compiling  $R_{eco}$  observations from both ambient and experimentally manipulated  
180 tundra ecosystems, as well as including extensive metadata on vegetation (e.g., plant community composition, functional traits, biomass), soils (e.g., pH, organic carbon and nitrogen content, soil organic matter), and microclimate (e.g., air and soil temperature, soil moisture). This structure enables users to categorise analyses according to ecosystem properties, environmental factors or experimental design. This supports hypothesis testing, model evaluation and the large-scale synthesis of tundra carbon–climate feedback.

### 2.2 Data sources and data collection

185 The TundraFlux Database compiles *in-situ* measurements of daily-aggregated terrestrial ecosystem-level  $CO_2$  fluxes ( $g\ C-CO_2\ m^{-2}\ day^{-1}$ ) from Arctic and alpine tundra ecosystems to assess warming effects on ecosystem  $CO_2$  respiration ( $R_{eco}$ ). We compiled data from experiments that used open-top chambers (OTCs) from across the Arctic and alpine tundra biome.

To achieve this, we contacted potential data contributors through established research networks like ITEX, WaRM, INTERACT and the Permafrost Carbon Network, and identified relevant contact information from authors of previously  
190 published meta-analyses on  $R_{eco}$  responses in warming experiments (Table S2).

We included data from experiments situated within the Arctic and alpine tundra biome (i.e., treeless regions beyond the climatic limit for tree growth) that reported *in-situ* measurements of ecosystem respiration ( $R_{eco}$ ) in both warmed open-top chamber (OTC) and unmanipulated control plots. Based on these criteria, we compiled 40,160 individual  $R_{eco}$  measurements,

encompassing repeated observations across multiple plots, years, days, and, in some cases, multiple measurement times within a day at each site.

To maximize data usability and harmonize temporal resolution across studies, we provide two interlinked versions of the  $R_{eco}$  dataset. The raw dataset retains all individual measurements at their original temporal resolution, including multiple measurements per day and associated quality-control information (in total 40,160 observations), allowing users full flexibility in data filtering and aggregation. In addition, we provide a daily-aggregated dataset in which  $R_{eco}$  values were averaged within each site (`site_id`), treatment (OTC or control), plot (`plot_id`), year (`flux_year`), and day of year (`flux_doy`) when multiple measurements occurred per day. This aggregation reduces short-term variability and preprocessing effort for synthesis applications, resulting in a total of 24,951 daily mean observations (OTC,  $n = 11,046$ ; control,  $n = 13,905$ ; Fig. 1E).

We define a *dataset* as all  $R_{eco}$  measurements from a given site and year (`site_id`  $\times$  `flux_year`), including both OTC and control treatments, all replicate plots, and one or more measurement dates (Table S3). Plot-level data were retained by design to preserve within-site replication and enable flexible, user-defined aggregation and statistical modeling approaches, including treatment-wise averaging or hierarchical analyses.

Alongside  $R_{eco}$ , we compiled *in-situ* metadata on microclimate conditions, geolocation, vegetation cover, plant traits, and soil characteristics. These ancillary variables were measured at both plot and site levels, with some recorded concurrently with flux measurements (and provided within the Carbon Flux data, Fig. 2), and others representing broader site-level environmental context that can be linked to the relevant flux measurements (Fig. 2, Fig. 3, Table S4).

Part of the database compiled through this effort was previously presented in Maes et al. (2024), which focused exclusively on growing season measurements (i.e., June to August) and included data up to the year 2020. This current published version of the TundraFlux Database extends the earlier synthesis by incorporating updated measurements through 2024 (Fig. 1B) and by including shoulder season fluxes from April to May and September to November (Fig. 1D).

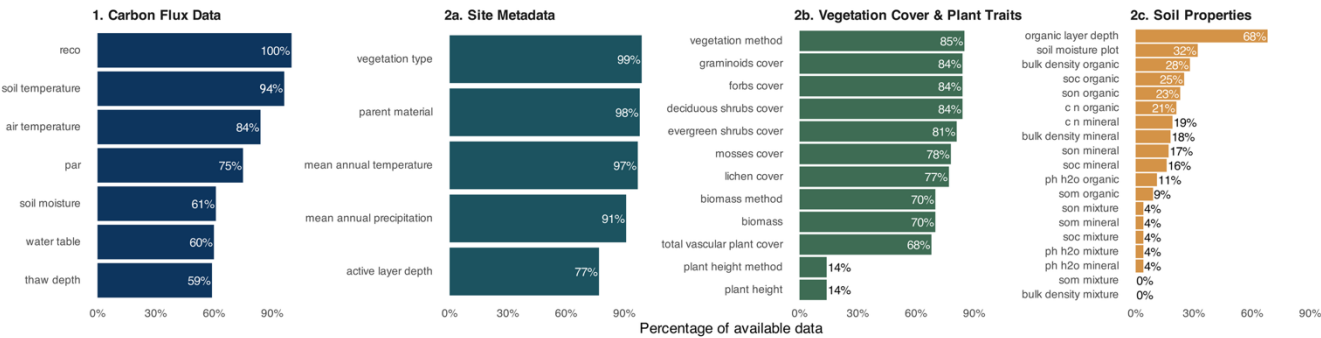
## 2.3 Data structure and variables

The TundraFlux Database comprises 76 variables describing  $R_{eco}$  from 64 tundra sites spanning 2000–2024 (Fig. 1A, B). A comprehensive data dictionary with a description of the variables of the site, vegetation, soil and method metadata, including data-type and unit is provided in the Supplements (Table S4).

# The TundraFlux Database

| 1. Carbon Flux Data<br>(plot-level)                                                                                                                                    | 2. Metadata                                                                                                                                                                                                     |                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                          |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| site_id<br>flux_date<br>flux_year<br>flux_doy<br>reco<br>treatment<br>plot_id<br>par<br>air_temperature<br>soil_temperature<br>soil_moisture<br>water_table            | 2a. Site Metadata<br>(site-level)                                                                                                                                                                               | 2b. Vegetation Cover & Traits<br>(plot-level)                                                                                                                                                                                        | 2c. Soil Properties<br>(plot-level)                                                                                                                                                                                                                                                                                                                      |
| 3. Method Metadata<br>(site-level)                                                                                                                                     | site_name<br>country_code<br>latitude<br>longitude<br>altitude<br>mean_annual_temperature<br>mean_annual_precipitation<br>active_layer_depth<br>parent_material<br>vegetation_type<br>PI_contact<br>add_contact | vascular_plant_cover<br>deciduous_shrubs_cover<br>evergreen_shrubs_cover<br>forbs_cover<br>graminoids_cover<br>lichen_cover<br>mosses_cover<br>vegetation_method<br>plant_height<br>plant_height_method<br>biomass<br>biomass_method | organic_layer_depth<br>bulk_density_organic<br>bulk_density_mineral<br>bulk_density_mixture<br>c_n_organic<br>c_n_mineral<br>soc_organic<br>soc_mineral<br>soc_mixture<br>son_organic<br>son_mineral<br>son_mixture<br>som_organic<br>som_mineral<br>ph_h2o_organic<br>ph_h2o_mineral<br>ph_h2o_mixture<br>soil_moisture_plot<br>soil_moisture_plot_type |
| measurement_method<br>machine<br>machine_type<br>flux_measurement_start_year<br>warming_start_year<br>plot_size<br>flux_plot_size<br>otc_height<br>chamber_temperature |                                                                                                                                                                                                                 |                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                          |

220 **Figure 2.** Data structure of the TundraFlux Database. Boxes represent the main data types: (1) Carbon flux data, including plot-level daily averages of ecosystem CO<sub>2</sub> respiration (R<sub>eco</sub>) in g C-CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup> and data measured along with flux measurements; (2) Metadata, including information on (a) site, (b) vegetation cover and plant traits at plot-level, and (c) Soil properties at plot level; and (3) Method data including documentation of experimental setups. Variables listed inside the boxes correspond to column names in the database (identical to Table S4).



225 **Figure 3.** Percentage of available observations for metadata variables presented in Figure 2 relevant for CO<sub>2</sub> modelling. Soil organic carbon (SOC), soil organic nitrogen (SON), carbon-to-nitrogen ratio (c\_n), soil organic matter (SOM).

## 2.4 Data standardization and quality control

Data were processed in R version 4.5.1 (R Core Team 2025). We used the R package TIDYVERSE (v. 2.0.0) for data handling. For each dataset, defined by a unique combination of site\_id and flux\_year, we calculated treatment- and plot-specific daily mean R<sub>eco</sub> values, whenever multiple measurements were made within the same day. We provide an R script on Zenodo (DOI: [10.5281/zenodo.17976235](https://doi.org/10.5281/zenodo.17976235)) that documents the full aggregation procedure, and the un-aggregated dataset (see the ‘Data

Availability' section). All individual flux measurements were standardized to a common unit ( $\text{g C-CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) to ensure comparability across studies. We screened the data for inconsistencies in unit or sign conventions, contacting data contributors in cases of uncertainty. Spatial coordinates were validated by visualizing all sites on a map, and any imprecise or conflicting locations were corrected in consultation with site researchers.

All experiments measured daytime  $R_{\text{eco}}$  using dark or opaque chambers, except for the CiPEHR site in Alaska (ALA\_1), where automated chambers continuously measured  $\text{CO}_2$  respiration using clear chambers. To obtain comparable respiration estimates for this site, we extracted only night-time fluxes, defined by photosynthetically active radiation (PAR) values below  $5 \mu\text{mol m}^{-2} \text{ s}^{-1}$ , as these best approximated dark chamber conditions. These night-time measurements were therefore used as the site's  $R_{\text{eco}}$  values.

The same quality-control procedures were applied to associated metadata to ensure consistency in spatial reference and measurement units across sites. Soil moisture data, reported at the plot level, were provided either as volumetric or gravimetric values and were subsequently converted to percentages. Bulk density was standardized to  $\text{g dwt cm}^{-3}$ . Soil organic carbon (SOC) and soil organic nitrogen (SON) were standardized to  $\text{g C kg}^{-1}$  soil and  $\text{g N kg}^{-1}$  soil, respectively, while soil organic matter (SOM) was standardized to percentages.

The TundraFlux Database includes occasional negative and exact-zero  $R_{\text{eco}}$  values (Table S3). These originate from the heterogeneity of measurement techniques and pre-processing procedures used in the studies that contribute to the database. Negative fluxes can occur in chamber-based measurements due to short-term  $\text{CO}_2$  concentration fluctuations, instrument noise, pressure-induced artefacts or brief periods of apparent net  $\text{CO}_2$  uptake when  $R_{\text{eco}}$  is close to the detection limit. We retained such values exactly as reported in the original datasets in order to preserve data fidelity. Exact-zero values appear when the net change in chamber  $\text{CO}_2$  concentration falls within instrument noise, or when contributors apply local preprocessing (e.g. rounding small negative fluxes to zero or applying minimum detection thresholds) prior to submission. As preprocessing conventions differed between studies, both negative and zero values are present in the compiled dataset. Users may apply additional filtering or thresholding, in line with their research objectives, for instance by removing negative fluxes, setting minimum detection limits or utilizing the quality control flags provided in the non-aggregated dataset.

#### 2.4.1 Outlier detection and handling

We chose not to filter outliers from the database before calculating daily averages to preserve the original data structure. However, recognizing the substantial variability in carbon fluxes across sites (Fig. 1E) and years (Table S3), we developed a tailored outlier detection and flagging procedure for  $R_{\text{eco}}$  data. This method applies the Median Absolute Deviation (MAD, Leys et al., 2013) to the non-aggregated  $R_{\text{eco}}$  values. This resulted in 285 flagged outliers (0.71% of the original 40,160 data points) and the user should consider whether to remove them or to use other criteria for outlier detection. We added a column to the non-aggregated dataset that indicates the flagged outliers. A full description of this method is provided in the Supplements. The R scripts used for data processing are archived on Zenodo (DOI: 10.5281/zenodo.17976235, Schwieger et

al., 2026) and are developed and maintained in a public GitHub repository  
265 ([https://github.com/SarahSchwieger/TundraFlux\\_Database](https://github.com/SarahSchwieger/TundraFlux_Database)).

### 3 Applications of the TundraFlux database

#### 3.1 Identifying extent and drivers of ecosystem respiration response to warming through meta-analysis

The TundraFlux Database is based on a global synthesis of how ecosystem respiration in Arctic and alpine tundra responds to experimental warming (Maes et al., 2024). Using 136 datasets from 56 OTC experiments at 28 tundra sites worldwide (60%  
270 of the data presented here), the study quantified that a mean rise of 1.4 °C [confidence interval (CI) 0.9–2.0 °C] in air and 0.4 °C [CI 0.2–0.7 °C] in soil temperatures causes a 30% [CI 22–38%] increase in growing season  $R_{eco}$ . It further showed that this stimulation persisted for up to 25 years of warming treatment, with evidence pointing to enhanced plant and microbial activity as the underlying drivers. By linking respiration responses to changes in local soil conditions (i.e., nitrogen concentration and carbon-to-nitrogen ratio), Maes et al. (2024) demonstrated that tundra sites with stronger nitrogen limitations  
275 and sites in which warming had stimulated plant and microbial nutrient turnover seemed particularly sensitive in their  $R_{eco}$  response to warming. This example highlights the power of standardized, long-term experimental data to uncover generalizable patterns in climate responses. It also showcases how the TundraFlux Database enables large-scale syntheses that identify not only the direction but also the mechanism of possible climate change feedbacks on tundra ecosystems, which are essential to improve carbon–climate feedback projections in Earth System Models.

280 The expanded TundraFlux Database, which now includes spring and autumn (‘shoulder-season’) measurements and updated observations through 2024, enables new high-impact research questions that could not be addressed in Maes et al. (2024). For example, users can quantify how experimental warming affects  $R_{eco}$  beyond the peak growing season and evaluate whether the environmental controls of  $R_{eco}$  differ between early-season, peak-season, and late-season periods. These additions substantially improve the capacity to analyze seasonal dynamics and long-term trajectories of tundra carbon cycling, thereby supporting  
285 more robust evaluations of climate–carbon feedbacks.

#### 3.2 Carbon model parameterization and validation

Accurately predicting carbon release from permafrost soils under warming scenarios remains a major challenge in climate science (Knoblauch et al., 2021; Schuur et al., 2015) due to the high variability in ecosystem responses and limited availability of long-term data (Swindles et al., 2015). The Warming Permafrost Model Intercomparison Project (WrPMIP) led by  
290 Woodwell Climate Research Center is using the TundraFlux Database to bridge the gap between experimental warming studies and large-scale carbon modeling ([warmingpermafrost.nau.edu](http://warmingpermafrost.nau.edu)). In this project, multi-model simulations are being run at both regional and site scales to align with the spatial and temporal dimensions of experimental data (Wells et al., 2023). By aligning field-based warming measurements from the TundraFlux Database with model simulations, the project will enhance our ability to project the magnitude and timing of carbon release from permafrost regions under climate change (Schädel et al., 2018).

As with any large database, not all biotic and abiotic variables, seasons, plant functional types, habitats, regions, or bioclimatic settings within the Arctic and alpine biomes are equally represented in the TundraFlux Database. Here, we identify some limitations related to gaps in the spatial and temporal resolution the database, which highlight clear priorities for future data collection efforts.

300 4.1 Spatial coverage and bias

The TundraFlux Database inherently reflects a sampling imbalance in the field, particularly the underrepresentation of key Arctic regions such as the Canadian High Arctic archipelago and Siberia (López-Blanco et al., 2024; Metcalfe et al., 2018; Virkkala et al., 2019; Fig. 1A, Table S5). Still it represents the most comprehensive effort that is currently available of  $R_{eco}$  data from warming experiments in the tundra. In particular, high-latitude North America and northern Europe are the best-  
305 represented regions (Table 1). This geographical concentration reflects a well-documented spatial bias in Arctic field sampling toward long-established research hubs with good accessibility and infrastructure (Metcalfe et al., 2018).

There is substantial variability in the number of measurements across sites (median = 120, IQR = 133.5; total measurements = 24,951). In particular, the CiPEHR site (ALA\_1) near Eight Mile Lake, Alaska, USA, with 13,572 daily-aggregated observations, contributed 52.5% of the  $R_{eco}$  data in the TundraFlux Database (Table S5). A large proportion of  
310 observations from a single, well-studied site increases temporal and treatment-level detail but may disproportionately influence cross-site or pan-Arctic analyses if not accounted for. How to address this imbalance depends on the user's research question and analytical framework, but several approaches can help prevent disproportionate influence of high-density sites. These include applying hierarchical or mixed-effects models that treat site as a random effect, using equal or inverse-effort site weighting, aggregating fluxes to common temporal resolutions, conducting sensitivity analyses (e.g., subsampling or excluding  
315 dominant sites), or using site-level bootstrapping or partial-pooling approaches (Choi and Kang, 2025). At the same time, these long-term, high-density datasets provide valuable opportunities for method development, uncertainty quantification, and benchmarking models at sites with robust metadata.

By systematically compiling data from OTC experiments across Alaska, Greenland, Svalbard, Iceland, Fennoscandia, Canada, and Russia, the TundraFlux Database is the most comprehensive resource currently available for evaluating warming effects  
320 on tundra carbon cycling. Importantly, tundra ecosystems exhibit substantial spatial variability in both abiotic and biotic conditions (Aalto et al., 2022; Magnússon et al., 2023), meaning that each site, regardless of data quantity, contributes distinct information about ecosystem responses under different environmental and vegetation contexts.

**Table 1.** Number and percentages of daily  $R_{eco}$  observations by region. See Table S5 for classification of sites into regions and distribution  
325 of individual sites across the regions.

| Region                       | Daily obs | %    | Nb of sites |
|------------------------------|-----------|------|-------------|
| High-latitude North American | 15,906    | 61.6 | 13          |
| Oceanic                      | 3,083     | 11.9 | 8           |
| High-latitude European       | 4,682     | 18.1 | 30          |
| Alpine European              | 479       | 1.9  | 5           |
| High-latitude Asian          | 542       | 2.1  | 3           |
| Alpine Asian                 | 1,136     | 4.4  | 4           |

## 4.2 Longer-term data on $R_{eco}$ response to experimental warming

In the TundraFlux Database, 93% of the averaged daily data points ( $n = 22,534$ ) come from warming experiments that lasted 11 years or less, and over half (51%, ( $n = 12,239$ )) lasted fewer than 4 years, at the time of  $R_{eco}$  measurements. At the time of publication, all warming experiments included in the database were still ongoing (Table S2). Out of the 64 sites in total, 7 sites (11.1%) represent long-term experiments with continuous measurements ( $\geq 5$  years), while 56 sites (88.9%) represent short-term experiments ( $< 5$  years) with often only single measurements (Table S5). Consequently, longer-term measurements ( $> 11$ -24 years) are rare ( $n = 1,573$ ), and data from warming experiments that lasted longer than 24 years are absent (Fig. 1C). This clearly highlights the importance of maintaining long-term experiments, particularly given that changes in soil processes or vegetation composition driven by warming may unfold over decades in Arctic and alpine tundra (Hollister et al., 2005; Jónsdóttir et al., 2023; Wei et al., 2025). At the same time, both OTCs and manual chamber measurements may introduce experimental disturbance effects (e.g., trampling, vegetation damage, soil compaction) that can accumulate over time (Hollister et al., 2023). Such disturbance may increasingly influence ecosystem functioning the longer an experiment runs. Thus, while longer-term data would help capture slow ecological changes, extended experiment duration may simultaneously amplify disturbance-related artefacts, complicating the interpretation of long-term trends.

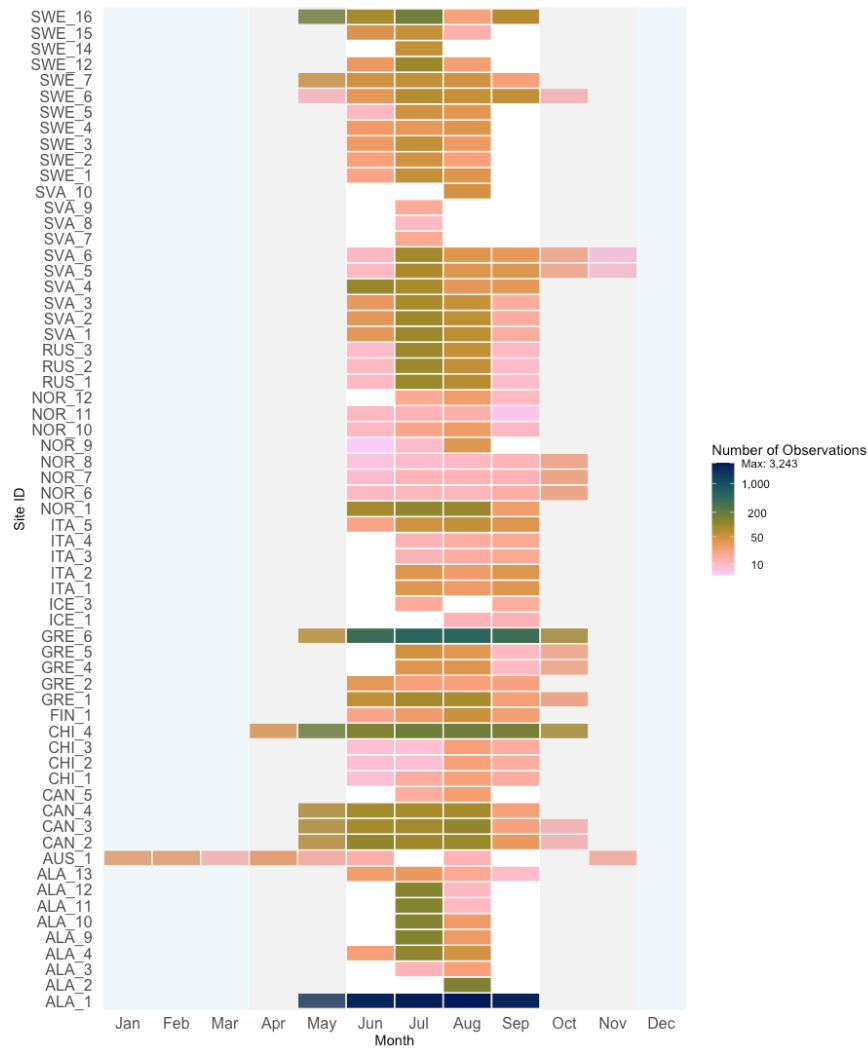
## 4.3 Shoulder and winter season respiration

Our database contains 21,830 daily-aggregated  $R_{eco}$  observations from the growing season (defined here as June-September in the Northern Hemisphere, and December-March in the Southern Hemisphere), and 3,297 observations from outside the growing season, highlighting a gap in our understanding of carbon fluxes in the shoulder (i.e., April, May, October, and November,  $n = 3,330$ ) and winter seasons (i.e., December-March in the Northern Hemisphere,  $n=0$ , Australia excluded) (Fig. 1D, Fig. 4).

As Arctic soils are usually covered in snow during the winter months, the spring and autumn shoulder seasons are particularly vulnerable to the effects of global warming, as these transitional periods experience rapid changes in snow cover and soil temperatures (Hassol, 2004; Shukla et al., 2019). Despite its length and significance, winter remains the most understudied season in Arctic ecosystems, even though cold-season processes can contribute substantially to annual carbon budgets through continued microbial activity and ecosystem respiration beneath the snowpack (Natali et al., 2019; Zona et al., 2016). Climate

warming is altering Arctic winters by increasing air and soil temperatures, changing snow accumulation and duration, and increasing the frequency of winter warming events and rain-on-snow events, all of which affect soil thermal conditions, microbial activity, and carbon fluxes (Cooper, 2014; Rixen et al., 2022). Similarly, alpine ecosystems are experiencing reduced snowpack, earlier snowmelt, and glacier retreat, with important consequences for soil temperature regimes, hydrology, and ecosystem functioning (Ernakovich et al., 2014). Warming effects and mechanisms identified during the growing season (Maes et al., 2024) may not apply to the winter season, when factors such as snow depth and duration exert great control over carbon fluxes (Björkman et al., 2010; Grogan, 2012; Morgner et al., 2010; Rixen et al., 2022; Semenchuk et al., 2016; Slatyer et al., 2022).

More research focusing on the effects of warming on carbon fluxes during the underrepresented winter and shoulder seasons while developing a mechanistic understanding of winter carbon dynamics is therefore essential to improve predictions of future CO<sub>2</sub> emissions from Arctic soils. Overlooking these seasons risks underestimating both the extent and variability of carbon release from rapidly warming Arctic soils.



365 **Figure 4.** Monthly  $R_{eco}$  availability aggregated across all years. White/ light grey/ light blue cells = 0 observations. Color intensity based on  $\text{Log}_{10}(\text{Number of Observations} + 1)$  due to strong bias of ALA\_1. Growing season = June–September in the Northern Hemisphere, December – March in the Southern Hemisphere. Except for AUS\_1, shaded areas indicate winter months (light blue) and shoulder months (light grey).

#### 4.4 Partitioning data

370  $R_{eco}$  responses to climate change depend on the dynamics of its two main components: autotrophic (plant-derived) and heterotrophic (microbial and faunal) respiration (Bond-Lamberty et al., 2004; Hicks Pries et al., 2013). Because these two components can respond differently to changes in climate (Borken et al., 2006; Muhr & Borken, 2009; Gomez-Casanovas et al., 2012), understanding their individual contributions is crucial to accurately predict ecosystem carbon dynamics and modeling carbon–climate feedback processes. However, partitioning  $R_{eco}$  into these source fluxes remains methodologically
 375 challenging. As respiration partitioning measurements are usually destructive, altering ecosystem dynamics and making long-

term measurements difficult, such data remain scarce. For example, in the meta-analysis on the drivers of  $R_{eco}$  in Arctic and alpine tundra by Maes et al. (2024), only nine out of 136  $R_{eco}$  datasets included partitioning data on the autotrophic and heterotrophic respiration components.

## 5 Future directions

380 In the coming years, our aim is to expand the scope of the TundraFlux Database beyond  $R_{eco}$  by incorporating methane and nitrous oxide fluxes, net ecosystem exchange (NEE), and gross primary productivity (GPP). We also plan to expand the scope of warming manipulations represented in the database by including additional climate change treatments, such as the use of snow fences to manipulate snow depth. This will enable us to distinguish between the effects of summer (OTC) and winter (snow fences) warming on  $R_{eco}$ , as well as the combined effects of these treatments (Hermesdorf et al., 2024). It will also allow  
385 us to account for cross-seasonal carry-over and the effects of coupled air-soil warming, whereby winter soil warming persists into summer and summer air warming can indirectly modify winter soil conditions via changes to vegetation (Kropp et al., 2020).

In recent years, remote sensing using unmanned aerial vehicles (UAVs) and satellites has advanced significantly, providing an opportunity to quantify landscape heterogeneity in the tundra biome at high spatio-temporal resolutions (Assmann et al.,  
390 2020; Myers-Smith et al., 2020). With this data, it is possible to bridge the gap between the TundraFlux plot-scale field measurements and large-scale remote sensing mapping products. In addition, we will incorporate remote sensing-derived metadata, such as tundra type and landform classification (e.g., peatlands, thaw slumps and coastal systems), as well as other derived products (Niittynen, 2026; Virkkala et al., 2024; Wagner and Hugelius, 2026), into future syntheses. Finally, we aim to link the TundraFlux Database with other available databases on terrestrial carbon fluxes (Table S1), including the Tundra  
395 Trait Team database (Bjorkman et al., 2018), the Manipulation Experiments Synthesis Initiative (MESI; Van Sundert et al., 2023), COSORE (Bond-Lamberty et al., 2020), and the ABCflux database (Leffler et al., 2025; Virkkala et al., 2022). Although integration remains challenging due to differences in data formats, identifiers, and metadata standards, establishing common protocols will be crucial to advance syntheses across databases.

To follow updates on ongoing and future projects related to our Tundra flux Database, please visit our website  
400 <https://arcticflux.org/>. To contribute new datasets, please contact us via our mail [tundrafluxdatabase@lists.umu.se](mailto:tundrafluxdatabase@lists.umu.se).

## 6 Conclusions

The TundraFlux Database provides the most comprehensive synthesis of tundra  $R_{eco}$  responses to experimental warming, integrating over 40,000 individual *in-situ*  $R_{eco}$  observations into 24,951 daily-aggregated  $R_{eco}$  measurements from open-top chamber and control plots across 64 Arctic and alpine sites. By combining these data with extensive environmental metadata,  
405 the database enables cross-scale analyses that link ecological processes to global carbon modeling. Although long-term (>24

years) data and measurements from outside the growing season remain limited, the TundraFlux Database establishes a foundation for coordinated synthesis and future expansion to include methane fluxes, NEE, and GPP. When linked with other ecological datasets, it will contribute to forming an unprecedented platform for cross-network analyses of Arctic and alpine carbon dynamics.

## 410 **Data availability**

The TundraFlux Database is organized as a set of interlinked R data files (.rds) that can be merged using shared identifiers such as site\_id, flux\_year, and, for plot-level data, plot\_id. For users who prefer a modular workflow, separate metadata files are available, including site (site\_metadata\_v1.rds), vegetation (plant\_metadata\_v1.rds), soil properties (soil\_metadata\_plot\_v1.rds), and methodological details (method\_metadata\_site\_v1.rds). These metadata files can be linked  
415 to Reco-specific datasets, such as Reco\_microclimate\_daily\_v1.rds, using the shared identifiers mentioned above.

For users who want a ready-to-use dataset, two fully integrated data files are provided: TundraFlux\_daily\_v1.rds, which contains daily aggregated Reco measurements along with site, vegetation, soil, and methodological metadata (Table S4), and TundraFlux\_raw\_v1.rds, which contains non-aggregated individual Reco measurements with quality-control flags.

Missing values are consistently represented as NA across all files.

420 All data is publicly available on Zenodo (DOI: [10.5281/zenodo.17976235](https://doi.org/10.5281/zenodo.17976235), Schwieger et al., 2026).

## **Code availability**

The code associated with this publication is publicly available on Zenodo (DOI: [10.5281/zenodo.17976235](https://doi.org/10.5281/zenodo.17976235), Schwieger et al., 2026). The R scripts used for data processing are archived alongside the data and are also maintained in a public GitHub repository ([https://github.com/SarahSchwieger/TundraFlux\\_Database](https://github.com/SarahSchwieger/TundraFlux_Database)).

## 425 **Supplement link**

### **Author contribution**

The TundraFlux database was conceptualized by JD, JS, ED, MB, and SLM. JD and SLM compiled the data in 2020. JD and SS updated the data in 2023 and 2025. Data screening and curation by JD, SLM and SS. SS drafted and coordinated the manuscript in close collaboration with SLM, JD, JS, BL, JW and MB. SS prepared the code and data files for the repository,  
430 revised by BL and JD. All authors contributed to the realization of the TundraFlux Database and participated in reviewing and editing of the manuscript.

# Competing interests

The authors declare that they have no conflict of interest.

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