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Soil drying with experimental warming depends on ecosystem type and warming method: First results of the Soil Warming to Depth Data Integration Effort (SWEDDIE)

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Abstract. Field-warming experiments offer insight into the response of ecosystems to rising temperatures, but cross-site comparison is needed to determine both the general tendencies of warming responses and the context dependencies of deviations from those norms. These responses are not limited to the direct effects of temperature but also their indirect effects on soil moisture, a critical factor controlling ecosystem productivity and carbon fluxes. Here we introduce SWEDDIE: the first global database to characterize the whole soil profile warming response across 26 distinct soil warming experiments, encompassing forest, grassland, cropland, tundra, and wetland ecosystems. SWEDDIE is needed because prior databases and syntheses of warming effects on ecosystems were dominated by aboveground warming studies, many of which warmed soil modestly or negligibly during much of the growing season and reported only growing season averages.

We demonstrate the potential of SWEDDIE by quantifying soil temperature and moisture changes for each experiment as a function of depth, warming methodology, ambient climate conditions, and ecosystem, as well as the relationship between soil moisture and imposed warming. Warming attenuated with depth at sites with aboveground warming only but increased with depth at sites with belowground warming only, as hypothesized. Warming led to soil drying at most sites, and drying was positively correlated with the magnitude of warming. However, the relationship between soil warming and soil drying varied by ecosystem: forest soils dried the most, while tundra soils became wetter with warming. Ambient climatic conditions also influenced the relationship between experimental warming and drying, with more drying per degree of warming observed in soils with higher ambient moisture.

The inconsistency of soil moisture changes with warming across ecosystems and warming methodologies demonstrates the importance of quantifying shifts in temperature and moisture in both space and time in order to overcome site-specific bias in ecosystem warming responses. The high temporal resolution and depth-resolved observations of the fundamental ecosystem properties of soil temperature and moisture in SWEDDIE v1.0.0 serve as a foundation for future experimental soil warming synthesis efforts and demonstrate the power of this actively growing community resource.

1 Introduction

Field warming experiments provide a unique opportunity to deepen understanding of how warming impacts specific ecosystem processes, yet insights from individual experiments are necessarily limited. For example, many experiments are limited in their duration, leading to omission or misconstruing of long-term processes (Melillo et al., 2017). Additionally, experiments employ a variety of warming methodologies, which has the potential to affect warming responses differently, e.g., differences in soil warming with depth could alter the relative impact of warming on above versus belowground processes (Aronson et al., 2009; Reich, 2010; Wang et al., 2019). Synthesizing data across multiple warming experiments, ecosystems, and warming methodologies, with explicit accounting for deep soil warming, is needed to quantify the general principles of ecosystem responses to rising temperatures as well as potential methodological biases. The Soil Warming to Depth Data Integration Effort

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(SWEDDIE) is a new database created to support such synthesis and provide guidance for the design and implementation of future field warming experiments.

The SWEDDIE database synthesizes data from the experiments of the DeepSoil2100 network of warming experiments. This network was formed to address the need for information on the warming response of the whole biologically active zone of the soil, and in recognition of the growing number of deep soil warming experiments and the potential for large knowledge advance through multi-site synthesis. (Torn et al., 2015; Protti-Sanchez et al., 2025). Recent evidence that top and subsoil C are equally vulnerable to warming induced losses (Hicks Pries et al., 2017) demonstrates the importance of considering whole soil warming responses. Roots, microbes, and critical biogeochemical processes continue well below 0.2 m in many soils (Hicks Pries et al., 2023), yet most warming experiments do not actively warm or observe soil below this depth. Including the response of deep soils to warming is additionally warranted as temperatures in near surface (≤ 0.01 m) and deep (≤ 1 m) soils are projected to increase at the same rate over the 20th century (Soong et al., 2020; Schmidt et al., 2001).

The results from warming experiments conducted over the past few decades document clear responses of soil processes and communities, such as biogeochemical cycling rates (Rustad et al., 2001; Bai et al., 2013; Lu et al., 2013), greenhouse gas fluxes (Yan et al., 2022), and biodiversity (Chung et al., 2013), as well as plant and animal communities (Warren et al., 2018; Singh et al., 2019; Stuble et al., 2021). Yet, at times these results are contradictory. Tropical soils, once thought to be relatively insensitive to warming (Koven et al., 2017), have shown unexpectedly large CO_2 emissions under experimental warming (Nottingham et al., 2020; Carter et al., 2020; Wood et al., 2025). Long term warming studies underscore the importance of the temporal dimension of warming responses, with large changes in effect sizes observed over years to decades (Melillo et al., 2017; Wang et al., 2019; Liang et al., 2024).

The response of soil respiration to warming is a major source of uncertainty in global soil carbon models. Soil moisture is one of the potential contributors to this uncertainty. Results from multiple studies, conducted at different field warming experiments, indicate that increased respiration fluxes in warmed soils only occur with adequate soil moisture. Furthermore, this moderating effect of soil moisture is consistent across both forest and grassland ecosystems as well as across latitudinal gradients (Flanagan et al., 2005; Hicks Pries et al., 2017; Reich et al., 2018; Yang et al., 2022; Liang et al., 2024). Accounting for the impact of soil moisture is therefore critical for interpreting the impact of soil warming in field experiments.

Previous research indicates that soils typically dry in response to experimental warming, although soil moisture responses to warming vary across ecosystem types, ambient climate conditions, and with depth (Xu et al., 2013). The potential impact of warming induced soil moisture changes is relevant given the importance of soil moisture in controlling ecological processes across scales. For example, recent work in a tropical forest warmed with infrared radiation (IR) heaters found soil moisture dominated over vegetation temperature in controlling plant physiological responses to warming (Carter et al., 2020). Similarly, soil moisture exerted a stronger effect on belowground C allocation than warming in a tallgrass prairie ecosystem (Xu et al.,

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2013). Soil moisture is also hypothesized to be one of the factors controlling potential microbial acclimation to warming, including shifts in carbon use efficiency (Allison et al., 2008; Manzoni et al., 2012). Indeed, a recent metanalysis of field warming studies found limited support for shifts in carbon use efficiency induced by warming alone (Zhang et al., 2024). Zhang et al. (2024) implicated soil moisture as a key constraint on microbial acclimation to warming but also pointed to the potential impact of warming methodology in explaining the observed variation in carbon use efficiency with warming. Warming methodology was also shown to be a critical factor influencing observed ecophysiological plant responses to warming in a recent metanalysis (Wang et al., 2019).

Various methods have been developed to manipulate soil temperature in field experiments. The most common approach to temperature manipulation in a field setting has involved the use of passive methods, such as passive open topped chambers (OTCs) (Hollister et al., 2022). These methods are inexpensive and result in minimal disturbance to the soil, yet the presence of the chamber confounds warming impacts on vegetation through alterations in canopy light penetration and herbivory, and can alter evapotranspiration rates as well (Aronson et al., 2009; Hollister et al., 2022). Aboveground IR heaters are a commonly applied approach to active warming that have the advantage of lower installation cost than resistance cable or rod installations (although typically with higher operational costs) (Aronson et al., 2009). Aboveground IR methods can warm both vegetation and soil, although the extent and depth of soil warming depends strongly on the vegetative cover. Additionally, aboveground IR methods may only warm soils outside of peak vegetation season due to canopy interception of IR (Rich et al., 2015). Belowground warming methods such as buried resistance cables or vertical rods have the advantage of heating soil more evenly over space and time, and enable warming to reach higher temperature targets that align with end- of- century predictions. However, installation and maintenance of belowground warming infrastructure is costlier and results in more disturbance to the soil compared to aboveground warming infrastructure (Peterjohn et al., 1993; Aronson et al., 2009; Rich et al., 2015; Torn et al., 2015; Hanson et al., 2017). Given the variety of warming methodologies employed across the experiments in SWEDDIE, as well as differences in the seasonality of imposed warming, the first step toward effective synthesis of these data is quantifying this variation along temporal and spatial gradients in a framework that facilitates quantitative comparison.

The goals of this paper are threefold: 1) introduce the SWEDDIE database, 2) quantify realized soil warming to depth across experiments and methodologies; and 3) demonstrate the potential of SWEDDIE by documenting the impacts of experimental warming on soil moisture. Specifically, we ask: does experimental warming lead to changes in soil moisture? How are potential soil moisture changes under experimental warming affected by ecosystem type, depth, warming methodology, and ambient soil temperature and moisture? This analysis of experimental warming efficacy and soil moisture change is intended to provide a baseline for future synthesis work, while simultaneously outlining the potential benefits and challenges of synthesizing in situ deep soil warming data.

We developed two hypotheses regarding the warming responses of soil temperature depth profiles and soil moisture, i.e., with respect to warming methodology, ambient climate conditions, and ecosystem type:

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1. Experimental warming will attenuate with depth at sites with aboveground warming only, increase with depth with belowground warming only, and be most consistent with depth with both above and belowground warming.
2. Soil warming will lead to soil drying, and: (a) the magnitude of soil drying in response warming will vary across ecosystems, and (b) the magnitude of soil drying in response warming will be greater in soils with higher ambient soil moisture, in line with current understanding of the physical relationship between soil moisture and evaporation.

2 Methods

2.1 Scope and experiment criteria

The SWEDDIE database (hereafter SWEDDIE) builds on data gathered from experiments in the DeepSoil 2100 network. The DeepSoil2100 network is a consortium of independently operated field soil warming experiments with a shared interest in the impacts of whole soil warming. From this perspective the ideal experiment is one in which a mean change in temperature ≥ +1 °C is measured at a depth ≥ 0.2 m over ≥ 1 y. Although not all the DeepSoil2100 experiments meet all these criteria, exceptions have been made on a case-by-case basis due to under-representation of the studied ecosystem or long experimental duration. We excluded experiments that used only passive OTC methods for soil warming, primarily because those methods do not warm the soil beyond ca. the top 0.1 m, and the magnitude of warming reported in the literature is inconsistent and variable (Hollister et al., 2022). Warming at all but two (Lyon Arboretum, Stillberg) of the 23 experiments in SWEDDIE is ongoing.

SWEDDIE consists of both publicly accessible and network-only data tiers. This approach is designed to maximize community engagement by lowering the barriers to data sharing within the network while promoting public data sharing for already published datasets. SWEDDIE is designed to be hosted by the Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE); ESS-DIVE is a web-based data repository that defines generalized metadata standards, as well as providing automatic generation of digital object identifiers (DOIs), data sharing and management, as well as querying and reporting tools (Agarwal et al., 2017). The SWEDDIE metadata standards meet the minimum ESS-DIVE requirements but with added requirements to meet the specific needs of a soil-focused ecosystem warming experiment database and to facilitate harmonization of variables within our data model. Data ingestion, manipulation tools, and both querying and reporting functionality for SWEDDIE are available in a companion R package, *sweddie* (Beem-Miller, 2026). However, these tools can be expanded to other coding languages or software environments in the future pending community interest and engagement.

2.2 Site characteristics

The SWEDDIE database is global in scope (Fig. 1). The database contains data from 23 experiments, covering a wide range of biomes and climate regimes (Table SI 1). The most represented ecosystems in SWEDDIE are temperate grasslands (n = 5) and forests (n = 5), followed by temperate coastal saline wetlands, tropical forest, and tundra (n = 3 each), then temperate

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croplands and boreal forest (n = 2 each), and lastly one boreal ombrotrophic peatland and one subtropical forest ecosystem. All but one experiment (FutureClim) is located in the northern hemisphere (Fig. 1).

Experiments in SWEDDIE employ a range of methods for warming soils (Table 1). Belowground warming methods include buried resistance cables and rods, as well as natural geothermal warming. Resistance rods are typically employed to accomplish deep soil warming, while resistance cables are typically used to improve uniformity of warming at the soil surface. In this study the term "resistance rod" refers to vertically installed stainless steel housing fitted with a length of resistance heating cable and packed with insulating material, e.g., sand. A few experiments only employ cables for belowground warming (Achenkirch, B4WarmED, Harvard Forest), while the ForHot experiment is unique in that the heated plots were warmed from below by geothermally heated groundwater (Sigurdsson et al., 2016).

Aboveground warming methods are more varied and include IR heaters, passive OTCs, active OTCs with forced air warming, and manipulation of soil insulation in winter via snow fences. IR heaters were the most common approach for aboveground warming. A few experiments deploy passive OTCs for seasonal aboveground warming in combination with belowground warming. Most experiments achieve warming with either belowground only (n = 11) or aboveground only (n = 4) methods, but several utilize both above and belowground warming methods (n = 8).

The mean duration of warming in across all manipulation experiments in SWEDDIE is 11 y (median = 9 y), with FutureClim the shortest (2 years) and Harvard Forest longest continuously monitored warming (34 y). The natural warmed geothermal experiment ForHot has a site with at least 60 y of documented warming, but regular monitoring was only initiated in 2008 (17 y).

Table 1 SWEDDIE experiments

	Warming						
Experiment	temp. range (n)	season	dur.	above	below	max. depth[1]	Additional treatments
	°C		y			m	
Experiment Station	1.5	all year	17	IR			+N
ACBB	4	all year	7		rods; cables	2.0	ecosystem; +N;
Achenkirch	4	growing season	21		cables	0.0	

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B4WarmED	1.7–3.4 (2)	growing season	17	IR	cables	0.1	canopy cover; ecosystem; -precip
Blodgett	4	all year	12		rods; cables	2.4	duration
CiPEHR	3	winter	18	snow; passive OTC			
ForHot	1–20 (5)	all year	18		geothermal	>3.0	duration; ecosystem
FutureClim	4	growing season	3	passive OTC	rods	0.8	-precip.
GENX	0.7–6.0 (8)	all year	3		cables	1.5	
Harvard Forest	5	all year	35		cables	0.1	+N
Lyon Arb.	4	all year	8		rods	2.5	
KAEFS	3	all year	17	IR			clipping; -precip.
MERIT	1.5–3.0 (2)	all year	7	passive OTC	cables	1.0	inundation
Point Reyes	4	all year	<1		rods; cables	2.4	
Sanming	5	all year	11		cables	0.1	+N
SMARTX	1.7–5.1 (3)	all year	9	IR	cables	1.5	eCO2; C3/C4
SPRUCE	2.3–9.0 (4)	all year	10	active OTC	rods; cables	3.0	eCO2
Stillberg	4	growing season	19		cables	0.0	eCO2; vegetation

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SWAMP	2	growing season	4	IR	rods	0.6	
SWELTR	4	all year	9		rods	1.4	
TEAM	4	all year	7		rods; cables	1.0	
TeRaCON	2.5	growing season	14	IR	rods	1.0	eCO2; +N; -precip.
TRACE	4	all year	9	IR			

[1] This is the maximum depth of belowground warming cables or rods.

2.3 Database

Individual ecosystem warming experiments are the fundamental unit of organization in the SWEDDIE database. All data in the database, i.e., each "entity", is therefore associated with a unique experiment. The database was designed to be flexible enough to incorporate any type of data including fluxes, soil properties, vegetation characteristics, sequencing data, etc. This flexibility is achieved via a unique hybrid data model defined by a combination of fixed-format (template-based) tables and open-format data tables (Fig. SI 1).

2.3.1 Core data

The database consists of three fixed-format "core" tables describing the experimental infrastructure (*experiment*), site characteristics (*site*), and experimental design (*plot*). In addition, the database contains an unlimited number of open-format observational measurement tables (*dat*), with one table per unique measured variable. The *dat* tables are linked to the core tables through primary keys, e.g., 'exp_name', 'sit_name', and 'plt_name', for the *experiment*, *site*, and *plot* tables, respectively. Detailed descriptions of all tables are provided in the supplementary information (SI Methods).

The *sweddie* R tools built to facilitate data ingestion currently rely on CSV file input, but this is a convention, not a requirement. The tools can be adapted as needed if other file formats are employed in the future, provided the file formats are non-proprietary in accordance with FAIR principles (Wilkinson et al., 2016).

2.3.2 Observations

Data observation (*dat*) tables are designed to be as simple as possible to facilitate harmonization and avoid duplication of variable names. Accordingly, each *dat* table is restricted to observations of a single variable (e.g., soil temperature, soil CO_2 flux, above ground biomass, etc.). These variables are semi-controlled, meaning that users are prompted with a list of previously used variable names during data ingestion (see "Scripted data ingestion" below). In addition to the observed data

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column, *dat* tables also contain a minimum of two required identification columns: the unique plot identifier (i.e., 'plt_name', which serves as a primary key and therefore must be an exact match with one of the 'plt_name' values in the *plot* table), and an observation date (timestamp) column. Depth-resolved data require at least one additional column to specify the depth at which the observation was made or paired upper and lower depth columns if measurements were made over a depth interval. Additional columns in the input data table are ignored and dropped during ingestion.

2.3.3 Metadata

Each *dat* table must be accompanied by a *data dictionary* (*_dd*) table describing the structure and contents of the *dat* table. The *_dd* table contains one row per column of the *dat* table. The first column of the *_dd* table lists the *dat* table column names; subsequent columns provide further information including: short text description, data type (i.e., numeric, string, etc.), semi-controlled variable name, units, method information, sensor make and model, and any notes relevant for data interpretation. Example templates for *dat* and *_dd* tables are provided in the supplemental information, along with a guide to assist with filling the tables.

Additional metadata associated with each *dat* file are stored in a separate *file level metadata* table (FLMD), one per experiment. The FLMD describes each *dat* file, including the data source, temporal coverage, missing value codes, target variable, versioning, and UTC offset. The design of the FLMD table is based on the guidelines provided by ESS-DIVE (Velliquette et al., 2021).

2.3.4 Scripted data ingestion

Data ingestion is a major challenge in database construction (Malholtra et al., 2019; Todd-Brown et al., 2022). Earlier soil database efforts tended to rely on highly structured templates explicitly defining allowable variables, data types, ranges, and names (Nave et al., 2017; Lawrence et al., 2020; Schaedel et al., 2020). While these templates reduce ambiguity, this comes at high manual labor cost. Template-based approaches are also error prone, requiring human transcription or custom scripts to accomplish the necessary translation of data into the required format (Todd-Brown et al., 2022). While the final output may be highly curated, the template-based approach is also relatively rigid, requiring a priori definitions of allowable variables and data categories.

Keyed translation is a more flexible alternative to the template-based approach that relies on a data dictionary to map input data with varying names and definitions onto a target set of names and definitions. This reduces the potential for transcription-based errors and preserves traceability of data transformations, but can be more computationally expensive, requires coding knowledge to generate data harmonization scripts, and can present data curation challenges in the absence of rigidly defined variables (Todd-Brown et al., 2022).

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We employed a hybrid data entry approach for SWEDDIE: using keyed translation to maximize flexibility for ingestion of observational data, but template-based data entry for relatively static data such as experimental design, infrastructure, or site characteristics, as this simplified the scripting process. As all data in SWEDDIE is derived from warming experiments; this provides a consistent framework for keyed translation with common data elements such as degrees of imposed warming, experimental design (i.e., plot identifiers), and timestamped data across all observational datasets.

The primary rationale for adopting the hybrid data model was to simplify the data submission process for data providers, as this is a common bottleneck in the data ingestion pipeline. We wrote semi-automated helper scripts to facilitate data harmonization, which is the next step in the data ingestion pipeline. The helper scripts create the required data dictionary and file level meta data files from raw observed data files via interactive console prompts. These scripts also output simplified and harmonized *dat* files if the raw input data do not conform to SWEDDIE standards. This simplification is accomplished by identifying the name of the target variables and splitting the input data table as needed, yielding a separate table for each variable. During this process the names of the other required identification variables (observation date, plot identifier, depth) in each *dat* table are harmonized to match standard names. All scripts were written in the R programming language and can be accessed by installing and loading the *sweddie* R package (Beem-Miller, 2026a). The package is under active development and for best results the latest (beta) version should be installed directly from Github (https://github.com/jb388/sweddie).

2.3.5 Data access

The latest version of the SWEDDIE database can be accessed from the project Github site: https://github.com/jb388/sweddie.

2.4 Quantifying soil warming

We addressed our first hypothesis regarding the impact of different warming methods on depth profiles of soil warming by quantifying observed warming over time and with depth. The duration of warming imposed throughout the year varied across the experiments, but we only considered data from the periods when the heating was active when quantifying warming. We also removed data from periods when the heating system was malfunctioning if this was reported. The majority of experiments (n = 16) undergo year-round warming, but several of the colder climate sites are only warmed during the growing season (Achenkirch, B4WarmED, FutureClim, Stilberg, SWAMP, TeRaCON). One experiment, CiPEHR, included passive OTC warming during the growing season, but warming was primarily achieved through the use of snow fences in winter. Despite this, we only quantified warming during the growing season in this experiment, as these were the only data available. Most, but not all experiments in the DeepSoil2100 network contributed soil temperature data. The exceptions are the Point Reyes experiment, which has been warming for < 1 y, and the ForHot experiment, for which soil temperature data were not available at the time of submission.

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Many of the experiments in SWEDDIE impose additional treatments beyond warming, such as elevated CO_2, modified precipitation, canopy cover, vegetation clipping, or nitrogen addition. While these treatments are recorded in the plot table and the data from these plots were ingested into the database, only data from the ambient temperature and warmed plots were used for the analyses presented here. The full range of treatments imposed in each experiment is detailed in Table 1.

We characterized soil temperature in each experiment over time and with depth for both ambient temperature (control) and warmed plots. We then computed the difference between warmed and control plots (ΔST) at each level of imposed warming. We first averaged temperature by depth for each experiment and treatment (warmed or control) at each time step; note that the frequency of observation varied across experimental sites. We then computed ΔST for each timestep by depth. In order to test our hypothesis about the impact of warming methodology on realized warming with depth, we calculated residual warming as the difference between expected and observed warming (Wr). Note that "expected" warming was defined in some experiments by the set-point for the thermostat controls but defined as the mean observed warming across all measurement depths for other experiments.

2.5 Quantifying soil moisture changes

Soil moisture is a critical variable influencing vegetation, the soil microbiome, and soil biogeochemical processes. We sought to test our second hypothesis that soil warming would lead to soil drying by first quantifying soil moisture in warmed and control plots and then computing the difference in soil moisture (warmed - control, ΔSM) over time and with depth for each site for the time periods. As with the soil temperature analysis, we only considered periods when soil was actively warming. We did not include soil moisture data from the saltwater marsh warming experiments in this analysis as soil moisture is determined by different factors in these ecosystems, and additionally, data were not available from most sites due to the challenge of measuring soil moisture in saline environments.

2.6 Bayesian generalized linear models

We applied a Bayesian generalized linear modeling approach (SI Eq. 1) to assess the impact of warming methodology on residual warming with depth (SI Eq. 2), and the relationship between observed soil moisture (ΔSM) and soil temperature differences (ΔST) across the sites (SI Eq. 3). The residual warming model included warming methodology, depth, and target warming temperature as fixed effects, as well as the interaction between depth and warming methodology. Due to the wide range of specific warming methods employed across the sites in SWEDDIE (Table 2), we recategorized this factor to distinguish between: above ground warming only, below ground warming only, or combined above and below ground warming; this enabled us to test our specific hypothesis that realized warming with depth varies among warming methods.

We tested our hypothesis that soil moisture changes due to warming vary across ecosystems by including ecosystem type in the ΔSM model as well as ambient climate conditions. We also included three interaction terms: ΔST by ecosystem type, ΔST

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by observed ambient soil temperature, and ΔST by observed ambient soil moisture. We also included the interaction between ΔST and observed ambient soil temperature and moisture in order to address our third hypothesis that the effect of ΔST on ΔSM would be enhanced under wetter and warmer soil conditions.

We used site as a random intercept term in both the ΔST and ΔSM models to account for differences in site level responses of ΔSM to ΔST. We also allowed the slope of the relationship between ΔSM and ΔST to vary across sites in the ΔSM model. Additionally, we included a temporal autocorrelation term in the ΔSM model to account for memory effects, i.e., day to day correlation in ΔSM, as well as a cyclical spline function to account for site-specific seasonal trends in ΔSM. Full model specifications and R code for the analysis are provided in the supplementary information (SI Methods).

A further challenge in assessing the potential impact of ΔST on ΔSM was that soil temperature and moisture observations were not made at the same depths or temporal resolution at all sites. We first averaged all soil moisture and temperature data by plot and depth at a daily timestep, as this was the minimum common temporal resolution of the dataset. We then filtered the data by site so as to retain only observations of soil temperature and moisture made on the same day. When the depth of observation differed between soil temperature and moisture, we fit a natural cubic spline function to soil temperature profiles and interpolated the soil temperature data to match the depths of observed soil moisture. We excluded any soil moisture or temperature observations exceeding the maximum observed depth of either variable to avoid inferring data beyond the depth support of the data.

All statistical analyses were performed in R (R Core Team, 2025). We used the R package “brms” (Bürkner, 2021) for the Bayesian generalized modeling, and additionally, the packages “emmeans” (Lenth, 2025) and “performance” (Lüdecke et al., 2021) for post hoc tests.

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3 Results

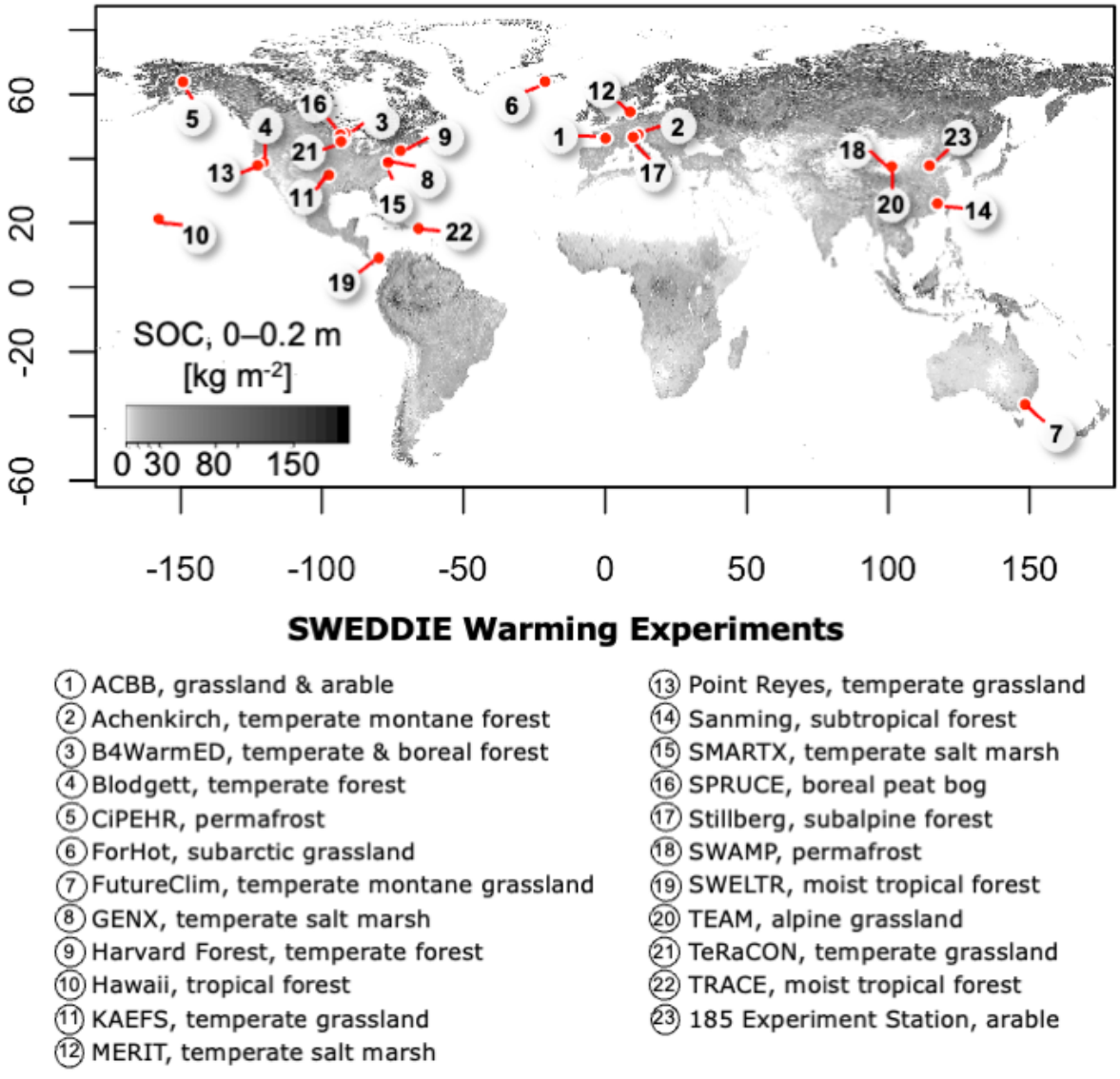

Figure 1 Map of SWEDDIE warming experiment locations. Red points are experimental sites; shading shows 0–2 m soil organic carbon stocks (kg m^{-2}) obtained from SoilGrids250 (Poggio et al., 2021).

3.1 Quantifying soil warming

Target soil warming ranged from +1 °C to +9 °C across all sites (n = 23). Observed warming tended to be cooler than target warming on average, but the magnitude of the divergence varied by degrees of warming, warming method, and depth (Fig. 2).

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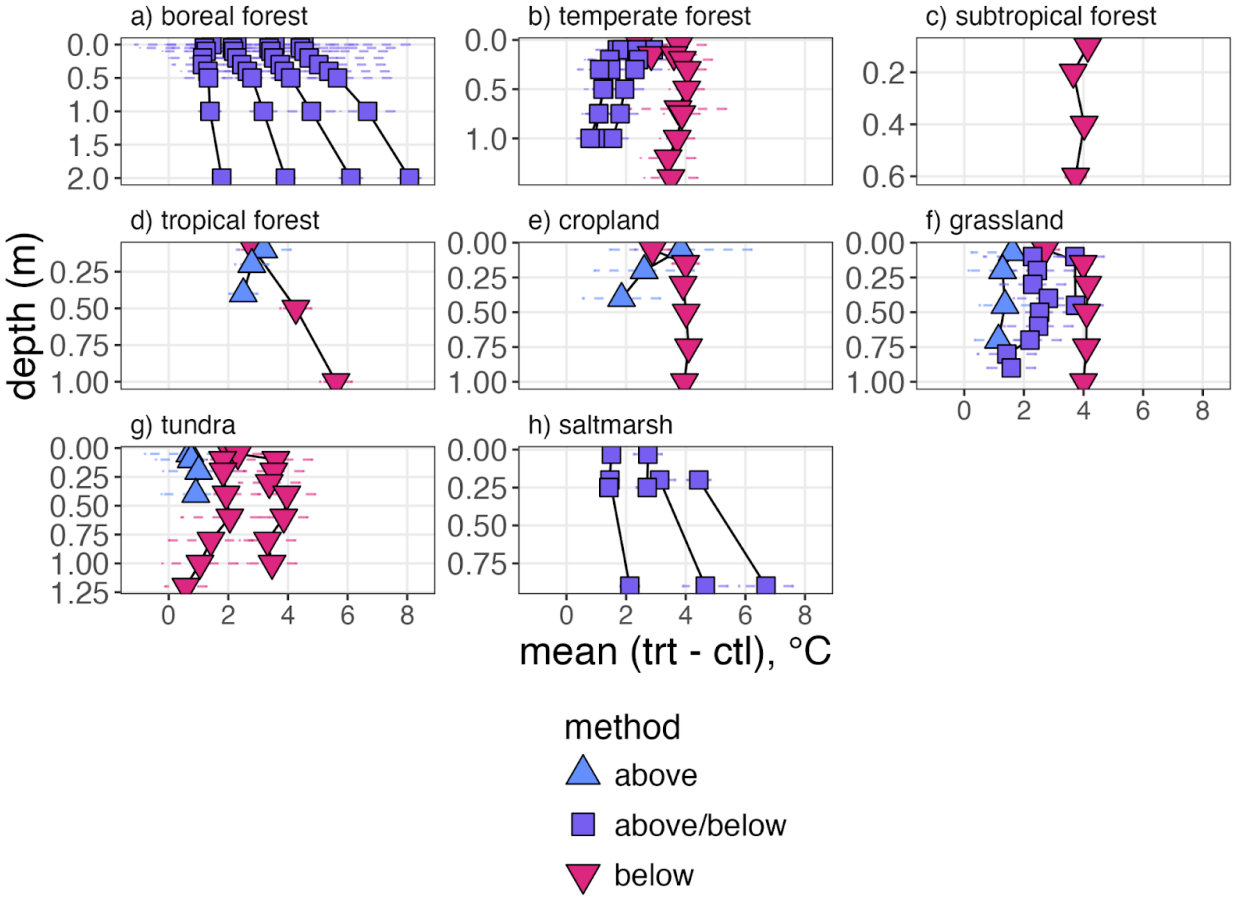

320 **Figure 2** Depth profiles of soil temperature differences. Points show means, error bars ±SD; trt: warmed; ctl : ambient. Notes: 1) y-axis values differ across plots, 2) sites with only a single observation depth excluded for clarity.

We observed substantial variation in the magnitude of warming with depth among warming methods (Fig. 2). Soils tended to be warmest at the soil surface in experiments with aboveground warming only, but warmest at depth in experiments with either below ground warming alone or combined above and below ground methods (Fig. 3). The Bayesian generalized linear model 325 for residual warming estimated a slight decrease in soil warming with depth with above ground only methods, and a slight increase in warming with depth in experiments warmed with belowground methods, although neither of these trends were significant (Fig. 3). The model results also indicated that achieving target soil warming becomes more difficult with increasing degrees of target warming, at a rate of -0.4 °C per degree of warming (Table SI 2).

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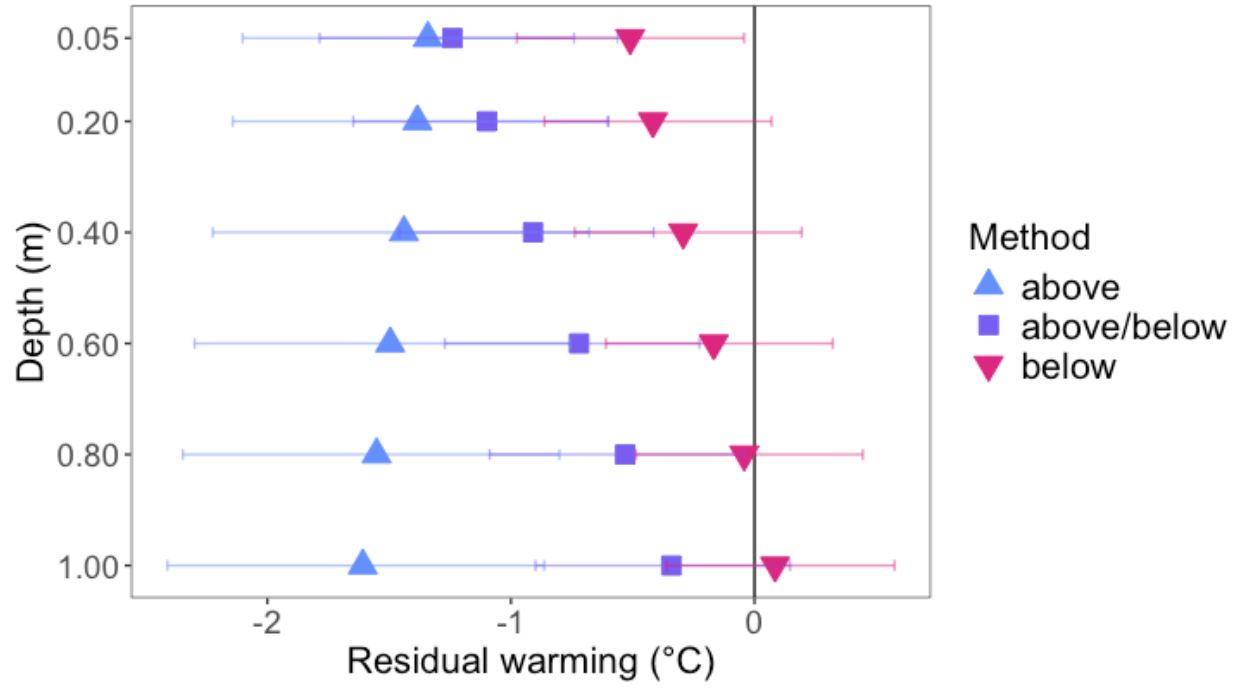

330 **Figure 3** Model estimated marginal means for residual warming (observed – expected °C) with depth by warming method. Residual warming estimated for +4 °C target warming; error bars show lower 5% and upper 95% highest posterior density interval.

3.2 Warming impacts on soil moisture

Warming led to drier soils in the majority of experiments, but with substantial variation among sites and across ecosystems
335 (Fig. 4). Soil moisture differences due to warming also showed substantial variation with depth (Fig. 5). Forest soils dried the most when compared across ecosystems, although this likely also reflects that degrees of warming tended to be higher in these ecosystems. The magnitude of soil drying was greatest in boreal forest soils and least in tropical forest soils when compared within forest ecosystem types. Grassland and cropland soils also tended to dry in response to warming, but not as consistently as forest soils. We saw the opposite trend of an increase in soil moisture with warming at four of the non-forest sites in cool to
340 cold climates: CiPEHR, SWAMP, TEAM, FutureClim. Soil moisture at the tundra sites (CiPEHR, SWAMP, TEAM) increased more than at the FutureClim grassland site (Fig. 5). Another commonality across two of these sites where soil moisture increased with warming (CiPEHR, FutureClim) was the use of passive OTCs for supplemental warming (Table 1), which were not employed at any of the other sites in this analysis.

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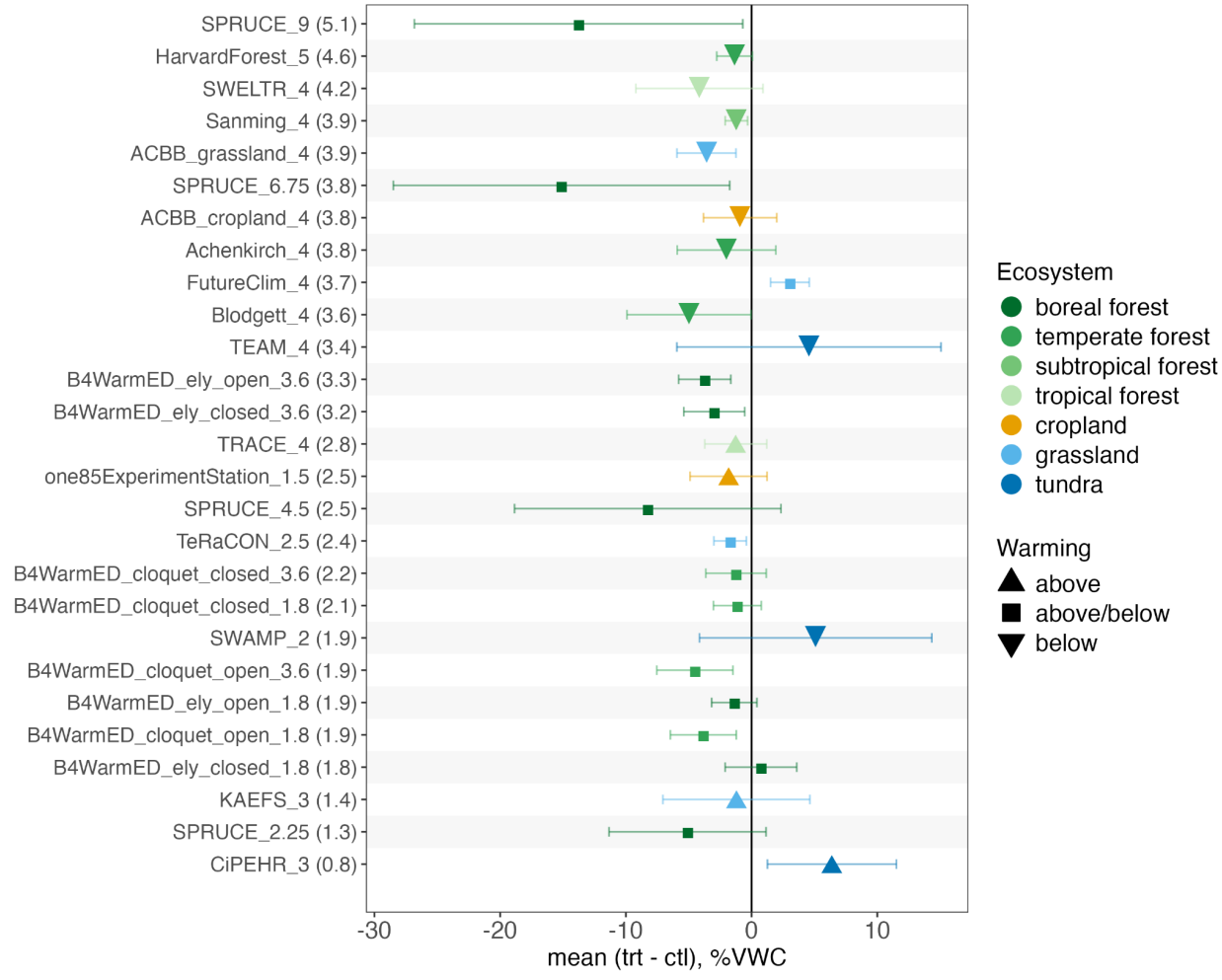

345 **Figure 4 Observed difference in soil moisture between warmed (trt) and ambient (ctl) temperature plots. Points show mean difference in volumetric water content (%VWC), averaged across depth and time; error bars show ±sd. Y-axis ordered by degrees of realized warming (shown in parentheses); target degrees of warming shown after underscore in site name. See Table 1 for details of warming methodology. Notes: 1) warming for the CiPEHR experiment was primarily conducted in winter, but realized warming is the mean for the growing season, 2) open/closed refers to canopy cover at the B4WarmED sites.**

350 Despite the trend toward soil drying observed at the forested sites, and the trend towards wetting at the tundra sites, ecosystem type was not a strong predictor of soil moisture change in the model (Table 2). The estimated median change in soil moisture with warming did not significantly differ from zero for any of the ecosystems when evaluated at the mean site conditions (Table 2). However, the model did indicate significant ecosystem level differences in both the direction and magnitude of soil moisture changes predicted per degrees of imposed warming (ΔST) (Table 2).

355 **Table 2 Estimated marginal means for the soil moisture model coefficients. Bold face indicates terms with 95% credible intervals excluding zero. Values are evaluated under the dataset mean conditions: +3.3 °C warming, 0.31 m depth, 38% VWC ambient soil moisture, and 9.9 °C ambient soil temperature. ΔST is the observed change in soil moisture.**

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Term	Slope	Credible interval		Intercept	Credible interval	
		5%	95%		5%	95%
boreal forest:ΔST	**-0.42**	**-0.61**	**-0.23**	1.34	-3.44	6.06
temperate forest:ΔST	-0.17	-0.71	0.37	-3.14	-14.68	11.22
subtrop. forest:ΔST	0.11	-0.33	0.56	-2.83	-10.78	7.81
tropical forest:ΔST	0.08	-0.26	0.43	3.60	-2.96	12.93
grassland	0.43	0.00	0.88	-2.27	-10.95	9.21
cropland	0.13	-0.17	0.42	-1.55	-11.36	10.80
tundra	-0.02	-0.23	0.20	1.25	-5.77	11.04
ambient soil moist.	**-0.07**	**-0.08**	**-0.06**			
ambient soil temp.	0.01	-0.02	0.04			
depth	0.01	0.00	0.03			

The change in observed soil moisture with warming was not strongly related to the degrees of imposed temperature change, in contrast to our expectations. It was only in the boreal forest soils that we observed a significant decrease in soil moisture with warming, at a rate of -0.4% VWC $°C^{-1}$ (95% HPD: -0.6, -0.2 %VWC $°C^{-1}$) (Table 2).

We saw a small but significant effect of ambient soil moisture on the magnitude of soil drying in the model, supporting our second hypothesis. The model estimate for this effect was a 0.07 (95% HPD: 0.06, 0.08) unit decrease in soil moisture (VWC%, defined as volume of water per volume soil) for every unit increase in ambient soil moisture (VWC%) (Table 2, Fig. SI 4). In context, this equates to an additional 1% of soil moisture loss for a relatively dry soil with 15% VWC, but a 6% increase for a relatively wet soil with 85% VWC. We did not observe a significant effect of ambient soil temperature on the change in soil moisture with warming (Table 2).

The conditional R^2 for the soil moisture model was 0.44, indicating that much of the variance in the soil moisture response to warming is not explained by the combination of degrees of warming, ecosystem, depth, and ambient climate conditions (Fig.

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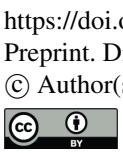

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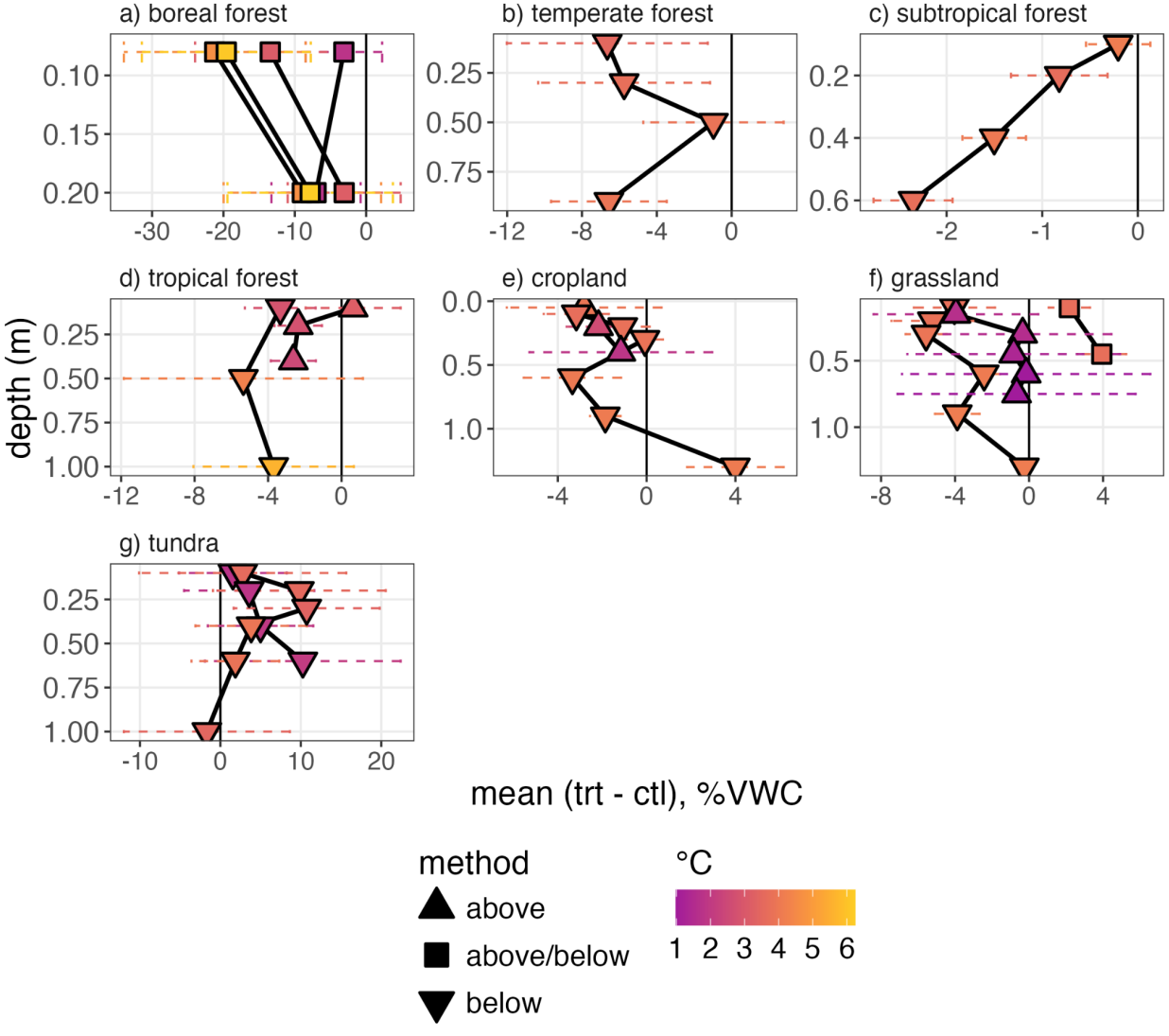
370 SI 3). We observed substantial variation in ΔSM with depth, although these trends were highly variable across sites (Fig. 5) and the effect of depth was only marginal in the model (Table 2). Partitioning of the explained variance indicated substantially more variation in ΔSM across sites (74%) than within sites (21%), and only a minor contribution in variance (5%) from site-specific ΔSM responses to degrees of imposed warming (Table SI 3).



375 **Figure 5 Observed soil moisture differences by depth. Points show means, error bars ±sd. Color indicates observed degrees of warming (°C). VWC: volumetric water content; trt: warmed; ctl: ambient temperature. Sites with only one depth of observation (i.e., Achenkirch, B4WarmED Cloquet, B4WarmED Ely, CiPEHR, Harvard Forest, and TeRaCON) excluded for clarity of depth trends.**

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Soil moisture changes due to warming showed distinct temporal trends, including minimal variation on a day-to-day basis across all sites, and site-specific seasonal offsets (Table SI 3). The seasonal offset term varied substantially across sites, suggesting a role for site-specific seasonal drivers of ΔSM beyond those considered explicitly as fixed effects or captured by the random slope and intercept terms (Fig. SI 2).

4 Discussion

Soil warming experiments provide critical information for understanding potential impacts of warming on ecosystem processes around the world. The question of how warming affects critical ecosystem services and processes is relevant across scales from microbial decomposition of soil organic matter to ecosystem scale drought to global atmospheric carbon exchange. Yet a great deal of uncertainty remains regarding belowground responses to warming, and this may be attributed in part to the uneven warming of biologically active soil layers that occurs in most experimental settings. Many published syntheses on soil warming responses rely on observations from studies in which passive OTCs were employed, a method that can in some contexts effectively warm air inside the chamber but does not provide consistent soil warming (Hollister et al., 2023). Aboveground IR based warming can effectively warm soils, especially when foliage canopies are not between the heaters and the soil, but as we demonstrate here, the warming effect attenuates with depth more than in experiments with below ground warming. It is important to quantify precisely how much the soil is warming across the soil profile if we are to constrain below ground warming responses more effectively when modeling warming responses of biogeochemical processes that extend into deeper soil layers. Furthermore, it is essential to quantify changes in soil moisture due to warming, given the importance of soil moisture for regulating biological activity and the high variation in soil moisture changes due to warming observed across the sites in this study.

Using the SWEDDIE database of deep soil warming experiments, we were able to quantify the magnitude of warming achieved in 23 warming experiments in six different biomes spread across the globe. This analysis revealed that regardless of the warming methodology applied at the individual experiments, the magnitude of warming varied with depth. This is not to be interpreted as a failure of experimental design, but rather as another reminder to quantify warming responses using observed, depth-resolved soil temperature data. In the context of synthesis, it is also important to use observed soil temperature data rather than stated target warming, as realized warming varied with depth even with active temperature control. Another point to clarify is that all warming methods were effective at warming soils, despite the relatively greater divergence from target warming temperatures (particularly at depth) observed with above ground only warming. For example, at the KAEFS site with above ground IR warming only, the soil temperature difference between warmed and ambient temperature plots reached the target of +2 °C at 0.1 m, but, notably, consistently measured >+1 °C at 0.7 m. At the other sites with above ground IR warming only (TRACE, 185ExperimentStation) the maximum depth of soil temperature measurement was 0.4 m, with observed mean warming of +2.5 °C and +1.9 °C respectively. It is important to note that the relative warming with depth achieved via above

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ground IR methods is particularly susceptible to seasonal fluctuations due to interference between foliage and the heaters, a phenomenon detected in SWEDDIE, but also previously demonstrated in the B4WarmED experiment (Rich et al., 2015).

Heat losses at the soil surface are the primary concern with belowground resistance cable heating. Recognizing this issue in earlier experiments motivated the installation of resistance cables at the soil surface at the Blodgett Forest site in addition to vertical resistance rods. This adaptation has also been implemented at the more recently built ACBB, TEAM, SWELTR, and Point Reyes experiments, demonstrating the practical benefit of cross-experiment collaboration. Despite the improved warming achieved with the combination of surface cables and buried resistance rods, experiments with this warming configuration still tend to have surface soil temperatures that are warmed less effectively than deeper layers (Fig. 4).

These differences in vertical warming gradients can be accounted for when assessing the temperature responses of soil processes by using depth resolved soil temperature data. Accounting for depth is particularly important when comparing warming responses across experiments warmed variably with aboveground only or belowground only method, as the variation in warming with depth may lead to differences in the relative response of above versus belowground processes. For example, an important component of the disagreement in global soil carbon model projections arises from uncertainty regarding the temperature sensitivity of soil organic matter decomposition. Given the evidence for soil carbon losses from deeper in the soil with experimental warming (Hicks Pries et al., 2017), variable warming of this vulnerable soil carbon reservoir due to differences in warming methodologies could lead to misinterpretation of the relative impacts of enhanced primary productivity versus decomposition on soil carbon stock changes in the coming decades, and the relative contributions of autotrophic versus heterotrophic sources to observed soil CO_2 fluxes. If these experimental manipulation results are to be useful in revealing the underlying soil biogeochemical mechanisms controlling soil carbon stock changes, and in turn to improve model projections, soil warming depth profiles must be quantified accurately.

Our second main goal was to quantify changes in soil moisture in response to warming. Unsurprisingly, soils tend to dry with warming, in line with our hypothesis and the findings of previous studies (Xu et al., 2013; Reich et al., 2018; Liang et al., 2024). Although warming tended to lead to soil drying, the relative drying response varied at the ecosystem level and with depth, suggesting potential ecosystem level controls on the relationship between soil drying and warming (Fig. 5). We observed clear differences in soil moisture with warming when evaluated at the site level, but these differences were not well explained by the combination of degrees of warming, ecosystem, or ambient climate conditions (Table 3, Fig. SI 3). The lack of explanatory power in these variables reflects the complexity of soil moisture responses to soil warming and demonstrates the importance of accounting for soil moisture changes explicitly when assessing ecosystem warming responses that may be affected by soil moisture.

We expected to find a positive relationship between the magnitude of warming and soil moisture change at the ecosystem level, but this was only the case for the boreal forest soils (Table 3). This may reflect the fact that this was the only ecosystem

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in which we had multiple experiments with more than a single warming level, minimizing the impact of site-specific interactions between magnitude of warming and soil moisture change. This illustrates the challenge of comparing warming responses across sites, especially in the context of non-linear temperature responses and ecological feedback (Kreyling et al., 2018; Leuzinger et al., 2015).

Earlier metanalyses of warming impacts on soil moisture showed stronger support for ecosystem level differences in soil moisture change than we observed, but similarly found that while many soils exhibit drying, others show increased soil moisture with warming (Xu et al., 2013). The substantial variation in soil moisture changes with warming observed in our data analysis may be due in part to the consideration of deeper soil layers, given that soil moisture varied substantially with depth in our dataset. The high temporal resolution of our dataset may have also contributed to the lack of significant differences in soil moisture changes at the ecosystem level, as we identified substantial site-level differences in the seasonal variation of warming induced soil moisture changes (Fig. SI 2)

Temporal shifts in the sensitivity of soil moisture changes to warming are relevant given the seasonality of many ecosystem processes. For example, if estimating warming effects on gross primary productivity, warming induced soil drying during the most active season of growth would likely have a greater impact than drying during annual periods of minimal plant productivity. The observed seasonal trends likely reflect local climate conditions, but also adaptations of the plant community to site-specific soil moisture conditions.

We would expect the relationship between soil moisture and warming to be non-linear from a theoretical standpoint. More evaporation is expected with higher energy input, i.e., under warming, but only when soil moisture levels remain in the range between the permanent wilting point and the critical moisture threshold (defined as the point at which soil moisture no longer influences latent heat fluxes) (Hsu et al., 2023). Through comparison to previous global analyses (Seneviratne et al., 2010) we estimate that most our sites fall within this transitional soil moisture regime, indicating that ambient soil moisture is likely to be a critical factor controlling evaporative soil moisture losses. Our model results support this theoretical relationship, with proportionally more drying observed in wetter soils given the same magnitude of warming.

Tundra ecosystems are a clear exception to the overall trend of warming induced drying. For tundra sites on permafrost, warming-induced thaw can lead to thermokarst collapse. This phenomenon has been documented at the CiPEHR experiment in SWEDDIE which is underlain by permafrost. The results in SWEDDIE confirm earlier findings of increased soil moisture in the warmed plots at CiPEHR but also demonstrate soil wetting with warming in the absence of thermokarst collapse at the other tundra sites (TEAM, SWAMP). The mechanisms behind the increase in soil moisture at these tundra sites and the FutureClim grassland site are not clear from the current dataset, but likely involve site-specific interactions, e.g., soil texture, potential influence of ground water or water infiltration outside the warmed plots, and non-temperature related factors influencing evaporative losses related to warming methodology.

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We focused on comparing aboveground, belowground, and combined above and belowground warming methods in this study. We were unable to compare specific warming methods (e.g., active OTC versus snow fences, etc.) due to the wide range of warming methods in use across the SWEDDIE experiments, and the fact that not all methods were represented in each ecosystem. However, from previously published work we know that aboveground warming methods can have divergent impacts on soil moisture changes. Specifically, active circulation of warm air in the enclosures constructed for the SPRUCE experiment was found to reduce relative air humidity, which in combination with warming led to shifts in the vapor pressure deficit, and in turn would be expected to increase evaporative soil moisture losses (Hanson et al., 2017). In line with this expectation, we observed the most substantial soil drying response at the SPRUCE experimental site. In contrast, the passive OTC warming method is known to increase relative humidity in the chamber headspace, which in turn would be expected to reduce evaporative soil moisture losses. Again, in line with this expectation, we observed increased soil moisture with warming at both sites that employed passive OTCs for above ground warming (CiPEHR, FutureClim). The mitigating effect of the passive OTC system on evaporative soil moisture losses may have contributed to the increase in soil moisture with warming observed at the FutureClim site, but not at any of the other non-tundra sites.

The variable effect of warming methodology on soil moisture changes is a useful illustration of both the power and the limitations of SWEDDIE for synthesizing ecosystem warming responses. A database with a relatively small number of sites will inevitably run into situations in which methodological effects cannot be effectively separated from site-specific variability, and this limitation must be assessed in combination with the available data when engaging in synthesis. However, the power of SWEDDIE lies in the potential to improve the quantification of warming responses across the entire biologically active portion of the soil profile, as well as how such warming responses may vary over subannual time scales. If we are to reduce the uncertainty in the predictions of future soil carbon stock changes, rates of nutrient cycling, or any other soil processes affected by warming, quantifying both realized warming and attendant shifts in soil moisture is a necessary first step.

The results of the soil moisture and temperature quantification presented here are a key building block of the next planned synthesis efforts: 1) using selected experiments to benchmark soil carbon warming responses with the *ecosys* model, and 2) quantifying soil CO_2 fluxes in response to warming. If, for example, future modeling work provides mechanistic insight into warming induced changes in soil carbon stocks, this could point towards future sampling and observation campaigns to test these mechanisms further. The goal of SWEDDIE is to stimulate active community engagement and increase data coverage, which in turn will enhance the capacity to generalize warming responses across ecological gradients, inform site- to global-scale models, and improve these valuable empirical datasets by accounting for potential methodological biases.

5 Conclusion

The SWEDDIE database is a unique community resource built with the aim of supporting synthesis of whole soil warming responses across ecosystems. We have also strengthened the DeepSoil2100 network through the process of data sharing, a

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network which has already proved instrumental for knowledge sharing about experimental design and implementation. We envision the soil temperature and moisture analyses presented here as both proof of concept and a foundation for future syntheses. These first soil temperature and moisture results demonstrate the scope and extent of baseline data coverage, and serve as a framework for growing the database with additional datasets. Given the importance of soil temperature and moisture for controlling biological activity across the soil profile, identifying and quantifying depth-explicit warming is an important first step for potentially reducing bias from shallow warming experiments that dominate the current literature.

Our results demonstrate that all warming methods were successful in warming soils, but that belowground methods warmed deeper soils more effectively and consistently. These methodological differences have important implications for assessing the relationship between warming and depth-dependent ecosystem processes, and these methodological differences must be accounted for to avoid bias in the interpretation of overall warming effects. For example, accounting for methodological differences on soil moisture or soil temperature depth profiles has important implications for assessing the impact of warming on soil carbon stock changes. Subsoils store a substantial amount of carbon, but the temperature sensitivity of decomposition in subsoils is poorly quantified relative to topsoils. Accordingly, we urge future synthesis efforts to use depth-resolved observations of soil temperature and moisture when it is possible, or to acknowledge the potential bias on ecosystem warming responses when they are not.

The direction and magnitude of soil moisture changes induced by warming varied across ecosystems in our study, trending towards drying in temperate and boreal forest soils, remaining unchanged in grassland and cropland soils, and wetting in tundra soils. The lack of a universal relationship between warming and soil moisture changes is unsurprising given the complex interactions between the atmosphere, vegetation, and soil that control soil moisture. Such variation in soil moisture responses to warming across the experimental sites in SWEDDIE underscores the importance of interpreting soil warming responses as the combined effects of temperature change on myriad biotic and abiotic processes in a specific ecosystem context. Uncovering the first principles that govern ecosystem level responses to warming requires actively pursuing multiple avenues of enquiry: well-controlled laboratory experiments to quantify temperature responses of specific processes, mechanistic models to assess the integrated impact of warming on multiple ecosystem processes, and observations from in situ experiments to constrain such models and inform future work. The value of the SWEDDIE database lies in the opportunity to compare observations of ecosystem warming responses that are too complex to be replicated in a laboratory. Realizing the potential of SWEDDIE to capture the temporal and spatial complexity of ecosystem warming responses in situ requires both quantifying experimental limitations as well as leveraging the power of synthesis.

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Data availability

Time series of soil temperature and moisture data from SWEDDIE used this manuscript are available at: https://doi.org/10.5281/zenodo.18237778 (Beem-Miller, 2026b). Tools for compiling and viewing SWEDDIE are available in the R package *sweddie*: https://doi.org/10.5281/zenodo.18190035 (Beem-Miller, 2026a).

Author contributions

J. Beem-Miller, W.J. Riley, P.B. Reich, M.S. Torn, M.W.I Schmidt, and A. Malholtra conceptualized the study, J. Beem-Miller, W.J. Riley, P.B. Reich, M.S. Torn, and M.W.I. Schmidt conducted developed the methodology and conducted the analysis, M.S. Torn and P.B. Reich acquired funding, Y. Bai, S.E. Crow, Z. Brown, R. Bermudez Villanueva, A. Chabbi, W. Dong, S.D. Frey, P.J. Hanson, K. Jensen, M.A. Knorr, E. Lathrop, P. Megonigal, A. Nicotra, A.T. Nottingham, G.L. Noyce, P.B. Reich, R.L. Rich, H. Rodenhizer, A. Sarquis, A. Schindlbacher, E.A.G. Schuur, Z. Shi, A. Stefanski, M.S. Torn, V. Unger, T.E. Wood, Y. Yang, Z. Yang, J. Zhou, and B. Zhu collected and provided data from soil warming experiments or are lead investigators at a SWEDDIE experiment. All authors contributed to manuscript preparation.

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Competing interests

The authors declare that they have no conflict of interest.

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