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Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- | | | |
|-------------------------------------|-------------------------------------|--|
| ☐ | ☒ | The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ | A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☐ | ☒ | The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☐ | ☒ | A description of all covariates tested |
| ☐ | ☒ | A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ | A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☐ | ☒ | For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☒ | ☐ | For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ | For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☐ | ☒ | Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	All data used for our analyses are publicly available. The data of field experiments were obtained at https://doi.org/10.6084/m9.figshare.24921495.v2 . Daily gross primary production (GPP) data were derived from ChinaFLUX at https://www.chinaflux.org/
Data analysis	Statistical analyses were performed in R version 4.3.0 (www.R-project.org) using open-source packages. The codes for modeling analysis are mainly performed in FORTRAN and are available in GitHub at https://github.com/wanggangsheng/MEND-FreezeThaw.git .

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

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Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	N/A
Reporting on race, ethnicity, or other socially relevant groupings	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study integrates multi-year soil warming experiment data from an alpine meadow on the northeastern Qinghai–Tibetan Plateau with the Microbial-ENzyme Decomposition model incorporating freeze–thaw dynamics (MEND-FT). The experiment included control and warming treatments (+4 °C soil temperature at 0–100 cm depth) with four replicated plots per treatment. Model simulations were constrained and validated using field observations of soil respiration, soil organic carbon, microbial biomass carbon, microbial C:N, inorganic nitrogen, microbial carbon use efficiency, and enzyme activities.
Research sample	The study focuses on soil microbial and biogeochemical processes in a seasonally frozen alpine meadow ecosystem (37°37' N, 101° 12' E; 3200 m a.s.l.) on the Qinghai–Tibetan Plateau. Vegetation is dominated by <i>Kobresia humilis</i> , <i>Kobresia pygmaea</i> , <i>Elymus nutans</i> , and <i>Gentian astraminea</i> . Soil is classified as Cryic Cambisol with loam texture. The dataset represents soil carbon and microbial dynamics in alpine meadow ecosystems under experimental warming.
Sampling strategy	Field measurements were collected from four replicated plots for each treatment (control and warming). Soil respiration measurements were conducted repeatedly during growing seasons across the experimental period. Soil chemical and microbial properties were sampled at fixed time points (August). Sample sizes were determined by the design of the long-term field warming experiment and established field protocols rather than formal statistical power calculations.
Data collection	Soil respiration, soil chemical properties, and microbial variables were measured in the field warming experiment following established protocols reported in the original studies. Environmental drivers used for model forcing (soil temperature, soil moisture, and GPP) were obtained from experimental measurements and the ChinaFLUX database. Additional microbial carbon use efficiency and enzyme activity data used for model validation were compiled from published studies conducted at the same site.
Timing and spatial scale	The warming experiment ran from June 2018 to September 2021. Soil respiration measurements were collected multiple times during growing seasons each year (May–September). Soil carbon and microbial properties were measured in August 2019 and August 2021. Microbial CUE and enzyme activities were measured in August 2021. Environmental forcing data were available daily. The study represents plot-scale processes within an alpine meadow ecosystem on the northeastern Qinghai–Tibetan Plateau.
Data exclusions	No data were excluded from the analyses beyond standard quality control procedures applied in the original datasets.
Reproducibility	The modelling framework (MEND-FT) was evaluated by comparing simulated variables with multiple independent observations including soil respiration, microbial biomass, microbial carbon use efficiency, and enzyme activities. Model simulations were performed using the same forcing data and parameter sets to verify reproducibility of results.
Randomization	Sampling on individual plots were successfully kept randomly.
Blinding	Not applicable, the study primarily involved process-based model simulations.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	The study site is an alpine meadow ecosystem on the northeastern Qinghai–Tibetan Plateau characterized by seasonally frozen soils. The mean annual air temperature is -1.1°C and the mean annual precipitation is approximately 485 mm, with about 80% of precipitation occurring during the growing season (May–September).
Location	Haibei National Field Research Station of Alpine Grassland Ecosystem, China ($37^{\circ}29' - 37^{\circ}45' \text{ N}$, $101^{\circ}12' - 101^{\circ}23' \text{ E}$, 3250 m a.s.l.).
Access & import/export	N/A
Disturbance	No long-term disturbance beyond the experimental treatments was introduced.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	N/A
Novel plant genotypes	N/A
Authentication	N/A