S1 Model descriptions

This supplementary document provides supporting information for the SPRUCE-MIP intercomparison. It includes detailed descriptions of the participating models, supplementary figures supporting the analyses presented in the main manuscript, additional methodological information, and illustrative parameter sensitivity figures for ELM-SPRUCE (Figs. S7-S8). A separate list of references cited in the Supplementary Materials is provided at the end of this document.

S1.1 CLASSIC

The peatland module of the Canadian Land Surface Scheme Including Biogeochemical Cycles (CLASSIC) is described by (Wu et al., 2016), with the full land model documented by (Melton et al., 2020; Seiler et al., 2021). The version used here (v1.5) includes coupled carbon and nitrogen cycling (Asaadi and Arora, 2021; Kou-Giesbrecht and Arora, 2022). Vascular plant productivity responds dynamically to nitrogen availability, whereas Sphagnum productivity remains independent of simulated nitrogen dynamics because moss Vcmax is prescribed and moss nitrogen is not mineralized. Model parameters were not specifically calibrated for the SPRUCE site but were adopted from previous peatland applications and the CLASSIC peatland benchmarking collection ((Melton et al., 2022; Wu et al., 2016)). Although CLASSIC includes the WETMETH methane model (Nzotungicimpaye et al., 2021), both the nitrogen and methane modules were disabled for the present SPRUCE-MIP simulations.

S1.2 CLM-Microbe

CLM-Microbe extends the CLM4.5 framework (Oleson et al., 2013) by incorporating a microbial functional group-based representation of methane production and consumption (Xu et al., 2015). The model explicitly represents dissolved organic carbon fermentation, hydrogenotrophic and acetoclactic methanogenesis, aerobic and anaerobic methanotrophy, and hydrogen production within the CLM4.5 decomposition framework (Koven et al., 2013). For SPRUCE-MIP, CLM-Microbe includes an explicit Sphagnum plant functional type with moss physiology (Shi et al., 2021), whereas hummock–hollow microtopography and lateral water transport were not represented.

S1.3 CoLM

CoLM2024 is the latest version of the Common Land Model (CoLM; (Dai et al., 2019b, a)). For SPRUCE-MIP, five plant functional types were represented, with C3 arctic grass serving as a surrogate for Sphagnum moss. Peat accumulation and methane processes are not explicitly represented. Plant growth is constrained by soil mineral nitrogen availability, with plant functional types competing for mineral nitrogen, soil water, and photosynthetically active radiation. Water-table depth is simulated from the local water balance, and carbon and nitrogen cycling include vertically resolved soil biogeochemistry and dynamic nitrogen transformations.

S1.4 CoupModel

CoupModel is a detailed process-based soil–plant–atmosphere model that simulates coupled water, heat, carbon, nitrogen, and phosphorus dynamics in terrestrial ecosystems (He et al., 2018, 2021; Jansson, 2012). The model represents a one-dimensional multilayer soil profile coupled to one or more vegetation layers and is driven by observed meteorological forcing. For SPRUCE-MIP, the model configuration was adapted from the Mer Bleue peatland application (He et al., 2023) with the addition of a tree layer. Observed water-table depth was prescribed to constrain hydrological conditions, whereas the nitrogen and methane modules were disabled during this intercomparison.

S1.5 DNDC

The DeNitrification–DeComposition (DNDC) model is a process-based biogeochemical model that simulates coupled carbon and nitrogen cycling in terrestrial ecosystems (Giltrap et al., 2010; Li et al., 1992). The Forest-DNDC version used in SPRUCE-MIP represents soil climate, vegetation growth, decomposition, nitrification, denitrification, and fermentation processes (Li, 2000; Stange et al., 2000). Plant growth is simulated through competition for light, water, and nitrogen among trees, understory vegetation, mosses, herbs, and lichens. Soil biogeochemistry explicitly represents organic matter decomposition together with methane production, methane oxidation, and nitrogen transformations, allowing simulated CO_2, CH_4, and N_2O emissions to respond dynamically to soil temperature, moisture, and substrate availability. For SPRUCE-MIP, the model was driven by observed meteorological and hydrological forcing following the standardized protocol described in Section 2.2.

S1.6 ELM-Microbe

ELM-Microbe extends an earlier version of the Energy Exascale Earth System Model (ELM) by integrating microbial methane dynamics with peatland-specific hydrology and vegetation processes (Ricciuto et al., 2021). The model combines previously developed representations of wetland hydrology (Shi et al., 2015), microbial methane cycling (Xu et al., 2015), and a *Sphagnum* plant functional type with explicit moss physiology (Shi et al., 2021). Relative to CLM-Microbe, ELM-Microbe additionally represents hummock–hollow microtopography and lateral hydrological exchange, while retaining the microbial functional group-based methane processes introduced by Xu et al. (2015). Methane emissions are simulated as the sum of diffusion, ebullition, and plant-mediated transport, with all pathways responding dynamically to soil temperature, substrate availability, and vegetation characteristics. Since 2019, ELM-Microbe has been further developed and parameterized using observations from the SPRUCE S1 bog, and has been applied to investigate peatland methane cycling under warming and elevated CO_2 (Ricciuto et al., 2021; Yuan et al., 2021).

S1.7 ELM-SPRUCE

The ELM-SPRUCE model used in this intercomparison is described by Shi et al. (2015, 2021) and is based on version 2 of the Energy Exascale Earth System Model (E3SM) land model (ELM) (Burrows et al., 2020; Golaz et al., 2019). Building upon earlier peatland developments implemented in ELM-Microbe, ELM-SPRUCE incorporates peatland-specific hydrology, explicit *Sphagnum* moss representation, lateral hydrological exchange between hummock and hollow microtopography, and a simplified treatment of long-term peat accumulation through vertical carbon and nutrient advection (Koven et al., 2013). Methane dynamics are represented using the CLM4Me framework (Riley et al., 2011). Key peatland parameters were developed and optimized using observations from the SPRUCE S1 bog (Shi et al., 2015, 2021). Four dominant plant functional types were represented: deciduous conifer (*Larix laricina*), evergreen conifer

(*Picea mariana*), deciduous shrubs, and a generic *Sphagnum* plant functional type. Spin-up, historical transient, and treatment simulations followed the standardized SPRUCE-MIP protocol described in Section 2.2.

S1.8 JULES

JULES (Joint UK Land Environment Simulator) (Best et al., 2011; Clark et al., 2011) is the land surface model component in the Unified Model (UM), it can be run both as a standalone model and coupled to the atmosphere in the UK Earth System Model (UKESM). JULES simulates coupled carbon, water, energy, and momentum exchanges between the land surface and the atmosphere. The model version used in this study is the JULES Earth System configuration (JULES-ES), evaluated by (Mathison et al., 2023). The setup includes representation of dynamic vegetation for 9 plant functional types (Harper et al., 2016), a 4-pool soil carbon model, nitrogen limitation evaluated by (Wiltshire et al., 2021) and a prognostic water table. A generic JULES-ES set-up was used, with no specific moderations made to the parameters, structural switches or diagnostics for SPRUCE-MIP, and therefore not tuned to the SPRUCE-MIP site. This model version does not represent acclimation, light response, Sphagnum moss or peatland specific structural components.

S1.9 LPX-Bern

LPX-Bern version 1.4 N is a dynamic global vegetation model that couples carbon, nitrogen, and water cycling (Joos et al., 2020; Lienert and Joos, 2018; Sitch et al., 2003; Spahni et al., 2013). Its peatland representation is based on LPJ-WHyMe (Wania et al., 2009b, a) with the addition of dynamic peatland area (Stocker et al., 2014). Carbon cycling is represented by distinct acrotelm and catotelm pools in the peat with dynamic water-table fluctuations controlling decomposition and methane production. Atmospheric CO_2, meteorological forcing, and nitrogen deposition were prescribed following the standardized SPRUCE-MIP protocol, with parameter settings based on Joos et al. (2020). Spin-up, historical transient, and treatment simulations followed the common protocol described in Section 2.2.

S1.10 LPJ-GUESS

LPJ-GUESS Peatland is a process-based dynamic peatland–vegetation model that extends the individual- and patch-based vegetation demography of LPJ-GUESS by explicitly representing peatlands as hydrologically regulated, carbon-accumulating ecosystems (Chaudhary et al., 2017; Smith et al., 2001). Vegetation dynamics emerge from competition among plant functional types for light, space, and soil water, while peat soils are represented by vertically accumulating carbon pools that simulate long-term peat development. The model explicitly represents methane production, oxidation, and emissions as functions of water-table position and soil thermal conditions and includes permafrost processes together with hummock–hollow microtopography. These coupled processes allow vegetation, hydrology, peat accumulation, and methane cycling to evolve interactively under changing environmental conditions (Chaudhary et al., 2017, 2020).

S1.11 MWM

The McGill Wetland Model (MWM) is a process-based ecosystem model developed to simulate carbon, nitrogen, and phosphorus cycling in northern peatlands (Shao et al., 2022; St-Hilaire et al., 2010; Wu et al., 2012). The version used in SPRUCE-MIP (MWMmic_NP) explicitly represents dynamic peat accumulation through annually formed peat cohorts, coupled carbon–nitrogen–phosphorus cycling, and microbial processes. The model includes two plant functional types (*Sphagnum* mosses and ericaceous shrubs) together with two microbial functional groups (saprotrophic microbes and ericoid mycorrhizal fungi) that regulate decomposition and nutrient exchange. Peat accumulation, vegetation dynamics, microbial activity, and nutrient cycling are simulated interactively, allowing the model to represent long-term peatland development and ecosystem carbon dynamics.

S1.12 ORCHIDEE-Peat

ORCHIDEE-Peat is the peatland-specific branch of the ORCHIDEE land surface model within the IPSL Earth System Model (Guimberteau et al., 2018). The model explicitly represents peatland hydrology and carbon dynamics using multilayer soil hydrology and soil carbon schemes with peat-specific hydraulic properties (Qiu et al., 2017, 2019). Long-term peat accumulation is simulated through downward transport of soil carbon, while decomposition responds to soil moisture, soil temperature, and peat depth. Spin-up, historical transient, and treatment simulations followed the standardized SPRUCE-MIP protocol described in Section 2.2.

S1.13 PTEM

PTEM version 2.3 is an advanced peatland ecosystem model that simulates coupled carbon and nitrogen dynamics in peatlands (Zhao et al., 2022b, a; Zhao and Zhuang, 2024). The model represents four plant functional types (Sphagnum mosses, herbaceous plants, shrubs, and trees), with vegetation composition regulated by water-table depth and nitrogen availability. Moss productivity is additionally influenced by shading from vascular vegetation. Peat carbon accumulation is represented using vertically resolved soil layers that simulate changes in peat bulk density and decomposition through both aerobic and anaerobic pathways, producing CO_2 or CH_4 depending on soil saturation. The model also includes coupled nitrogen cycling, including mineralization, plant uptake, nitrification, denitrification, deposition, and biological nitrogen fixation. Water-table depth is simulated using a TOPMODEL-based approach and subsequently drives coupled vegetation, peat carbon, and nitrogen dynamics, allowing interactions among productivity, decomposition, and methane emissions to emerge over time. Spin-up, historical transient, and treatment simulations followed the standardized SPRUCE-MIP protocol described in Section 2.2.

S1.14 TECO-SPRUCE

TECO-SPRUCE is based on the Terrestrial ECOsystem (TECO) model (Weng and Luo, 2008), which simulates coupled carbon and nitrogen cycling using multiple vegetation, litter, and soil carbon pools. For SPRUCE-MIP, the model was extended to represent soil thermal dynamics (Huang et al., 2017), water-table fluctuations, methane cycling, and parameterizations specific to the SPRUCE experiment. Historical forcing was derived from the CRUNCEP v7 dataset (Viovy, 2018), whereas the experimental simulations followed the standardized SPRUCE-MIP protocol using the observed SPRUCE forcing data. Spin-up, historical transient, and treatment simulations were conducted following the procedures described by the TECO-SPRUCE development team.

S1.15 VISIT

VISIT (Vegetation Integrative Simulator for Trace Gases) is a process-based terrestrial ecosystem model that has been widely applied to regional and global methane budget studies (Ito, 2019; Ito et al., 2023; Ito and Inatomi, 2012). The wetland methane module is based on (Walter and Heimann, 2000) and represents methane production, oxidation, and emissions through diffusion, ebullition, and plant-mediated transport. Soil biogeochemistry is represented using a multilayer soil profile, while water-table depth is prescribed. For SPRUCE-MIP, meteorological forcing followed the standardized experimental forcing dataset, whereas vegetation productivity was simulated using the VISIT carbon cycle model with parameters representing evergreen coniferous forests.

S2 Supplementary figures

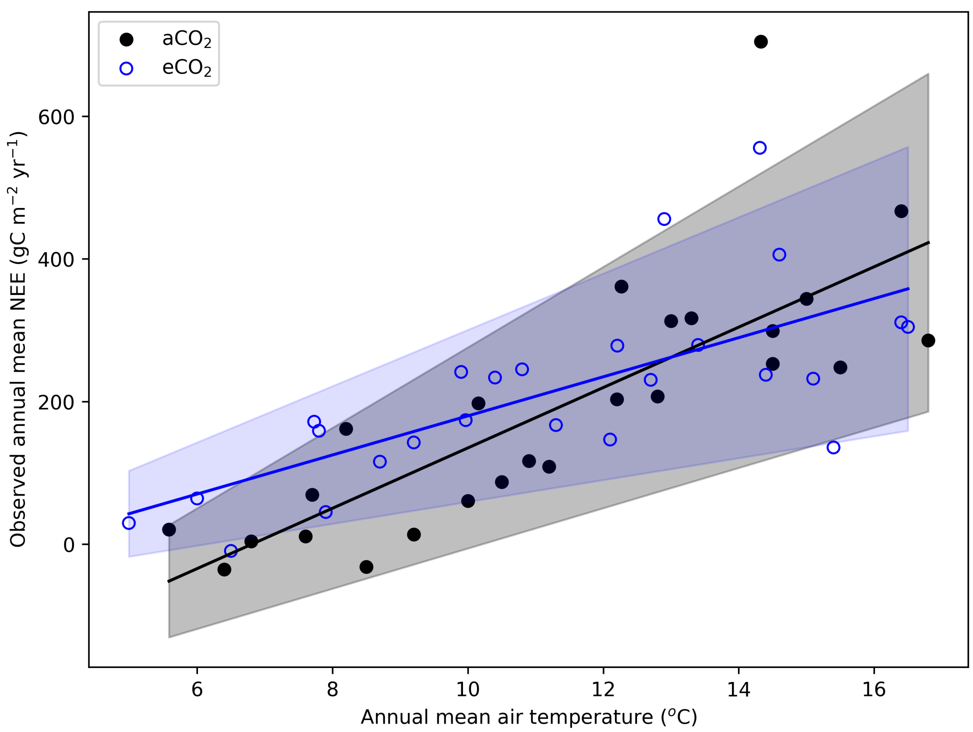

Fig. S1. Example of the regression-based estimation of temperature sensitivity for observed NEE. Annual mean NEE is plotted against annual mean air temperature under the aCO_2 and eCO_2 treatments. Solid lines indicate the least-squares linear regressions used to estimate temperature sensitivities, and shaded regions represent the 95% confidence intervals of the fitted regressions. The regression slopes correspond to the observed temperature sensitivities reported in Fig. 4a.

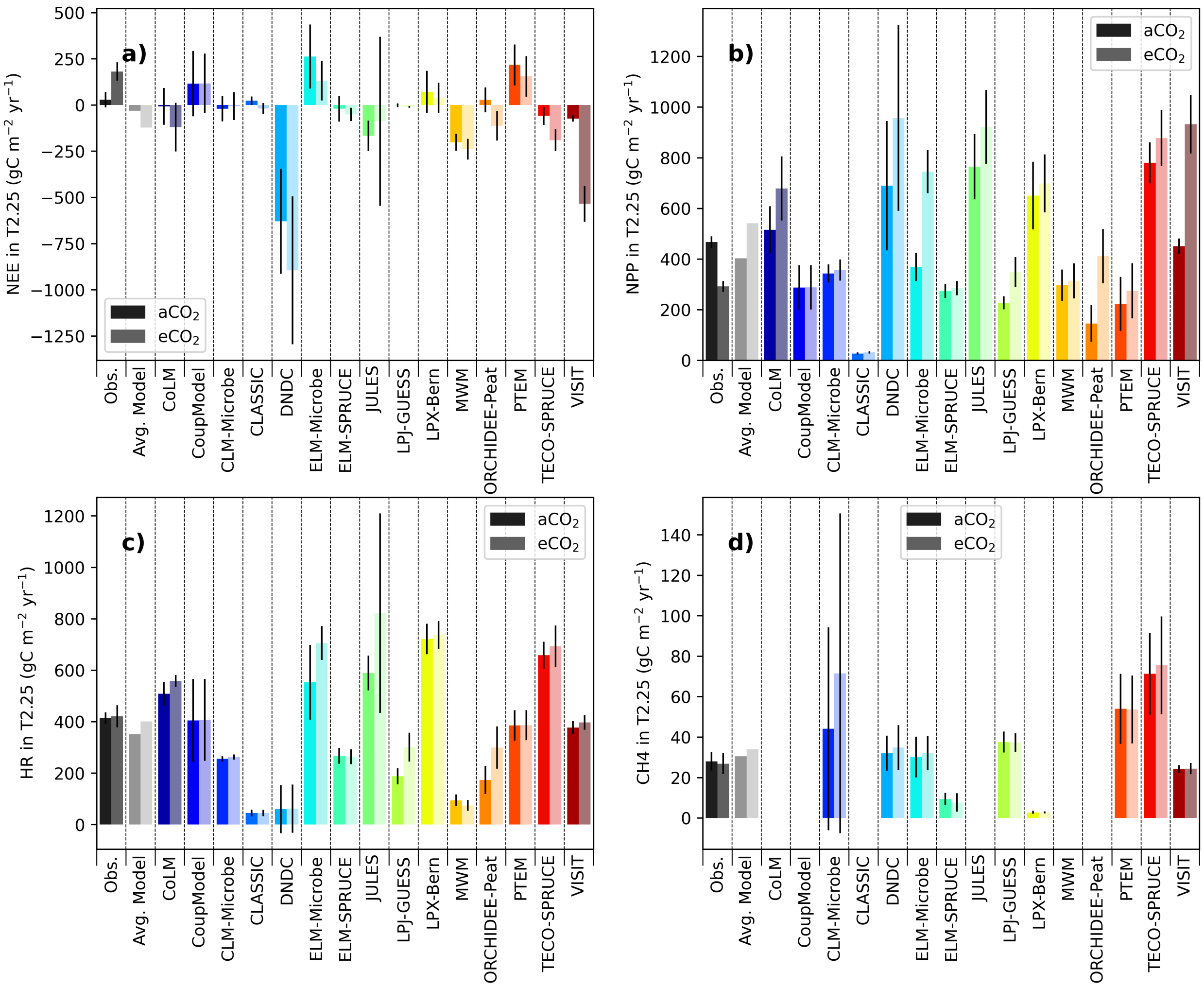

Fig. S2. Simulated a) NEE, b) NPP, c) HR and d) CH_4 compared with observed (Obs) values under the +2.25 °C warming treatment at aCO_2 and eCO_2 conditions. Bars represent multi-year means (2015-2021), and error bars denote interannual standard deviations of annual values. Note that NEE includes the carbon equivalent of CH_4 emissions to account for their contribution to changes in peat carbon stocks.

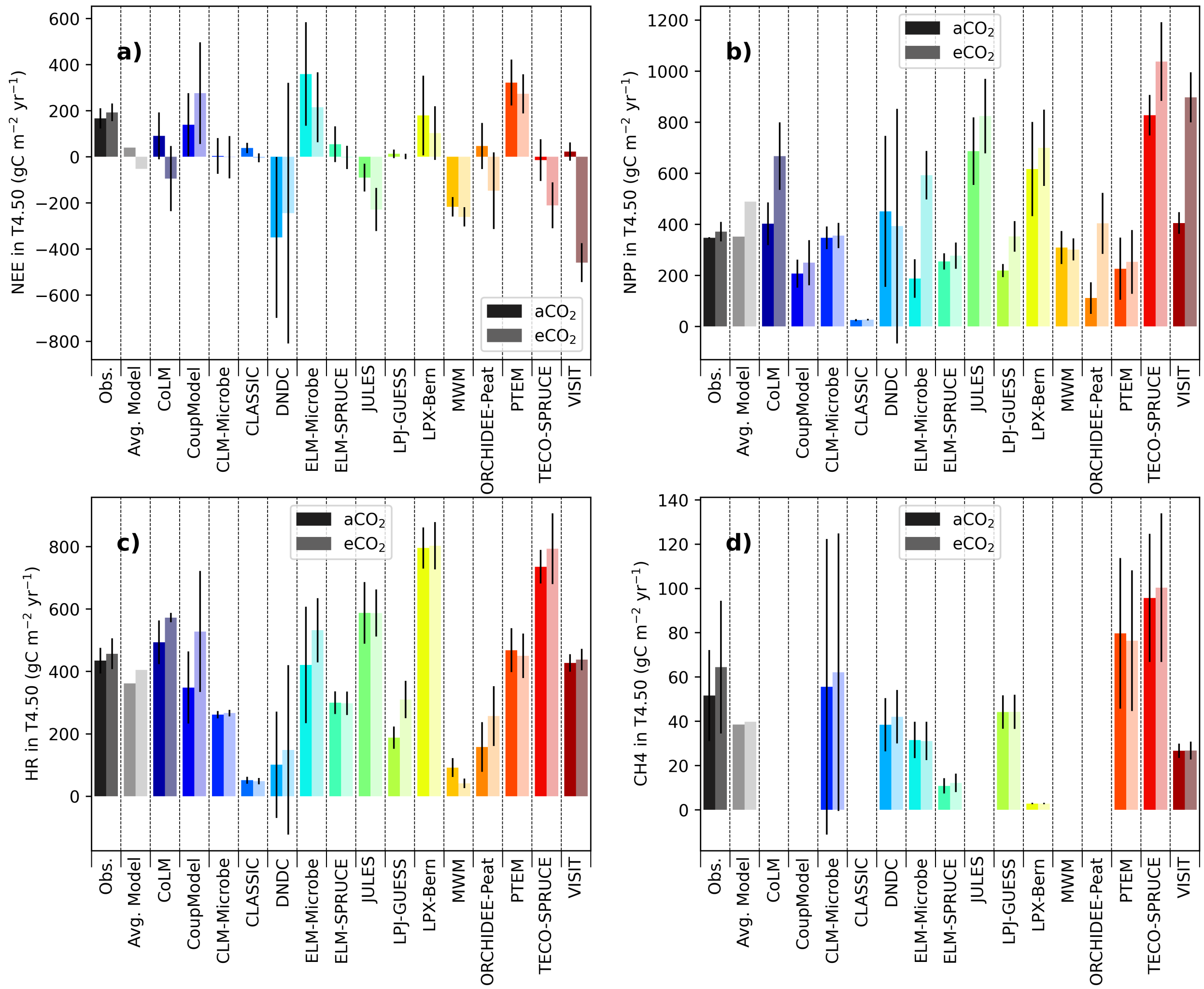

Fig. S3. Simulated a) NEE, b) NPP, c) HR and d) CH_4 compared with observed (Obs) values under the +4.50 °C warming treatment at aCO_2 and eCO_2 conditions. Bars represent multi-year means (2015-2021), and error bars denote interannual standard deviations of annual values. Note that NEE includes the carbon equivalent of CH_4 emissions to account for their contribution to changes in peat carbon stocks.

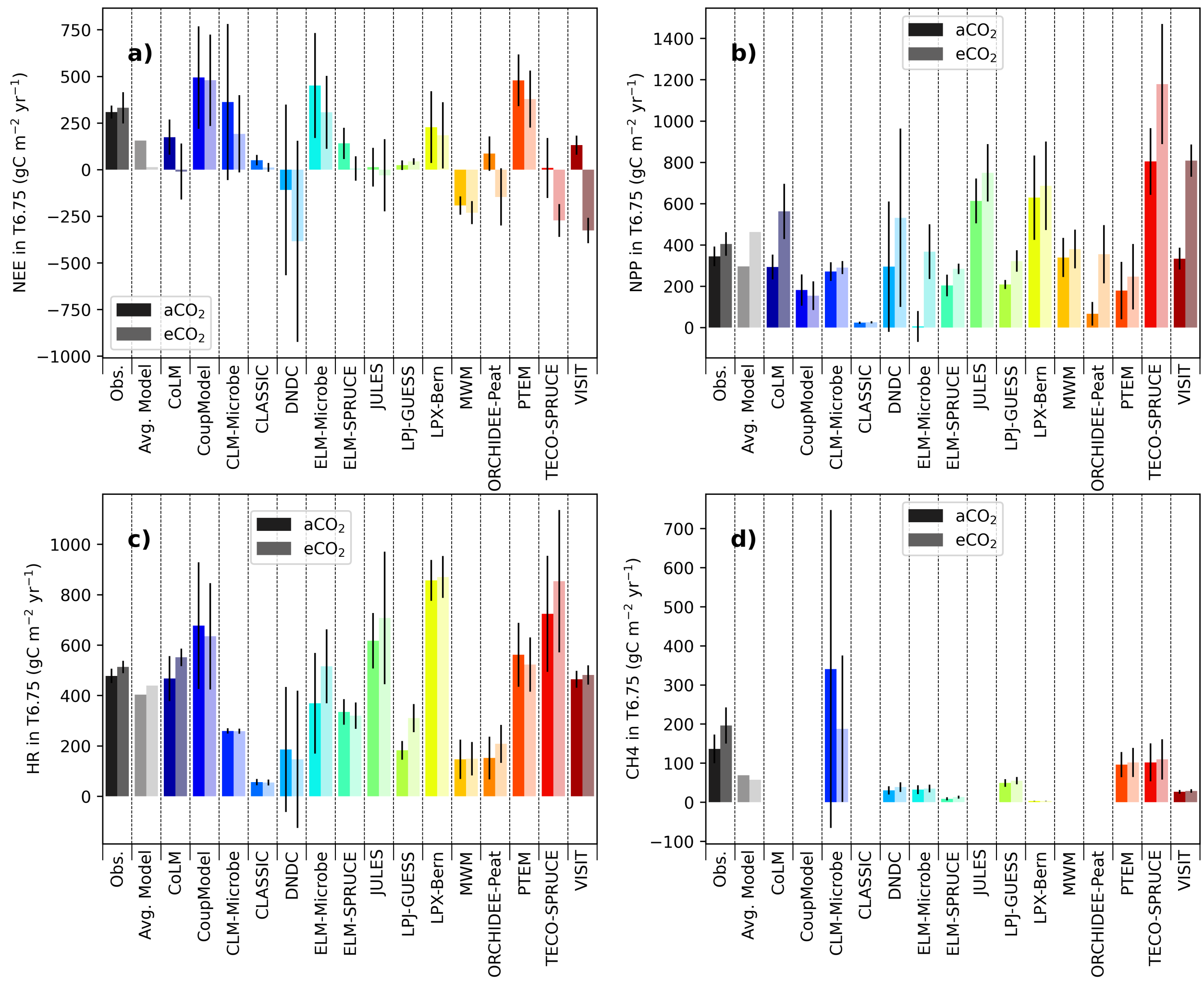

Fig. S4. Simulated a) NEE, b) NPP, c) HR and d) CH_4 compared with observed (Obs) values under the +6.75 °C warming treatment at aCO_2 and eCO_2 conditions. Bars represent multi-year means (2015-2021), and error bars denote interannual standard deviations of annual values. Note that NEE includes the carbon equivalent of CH_4 emissions to account for their contribution to changes in peat carbon stocks.

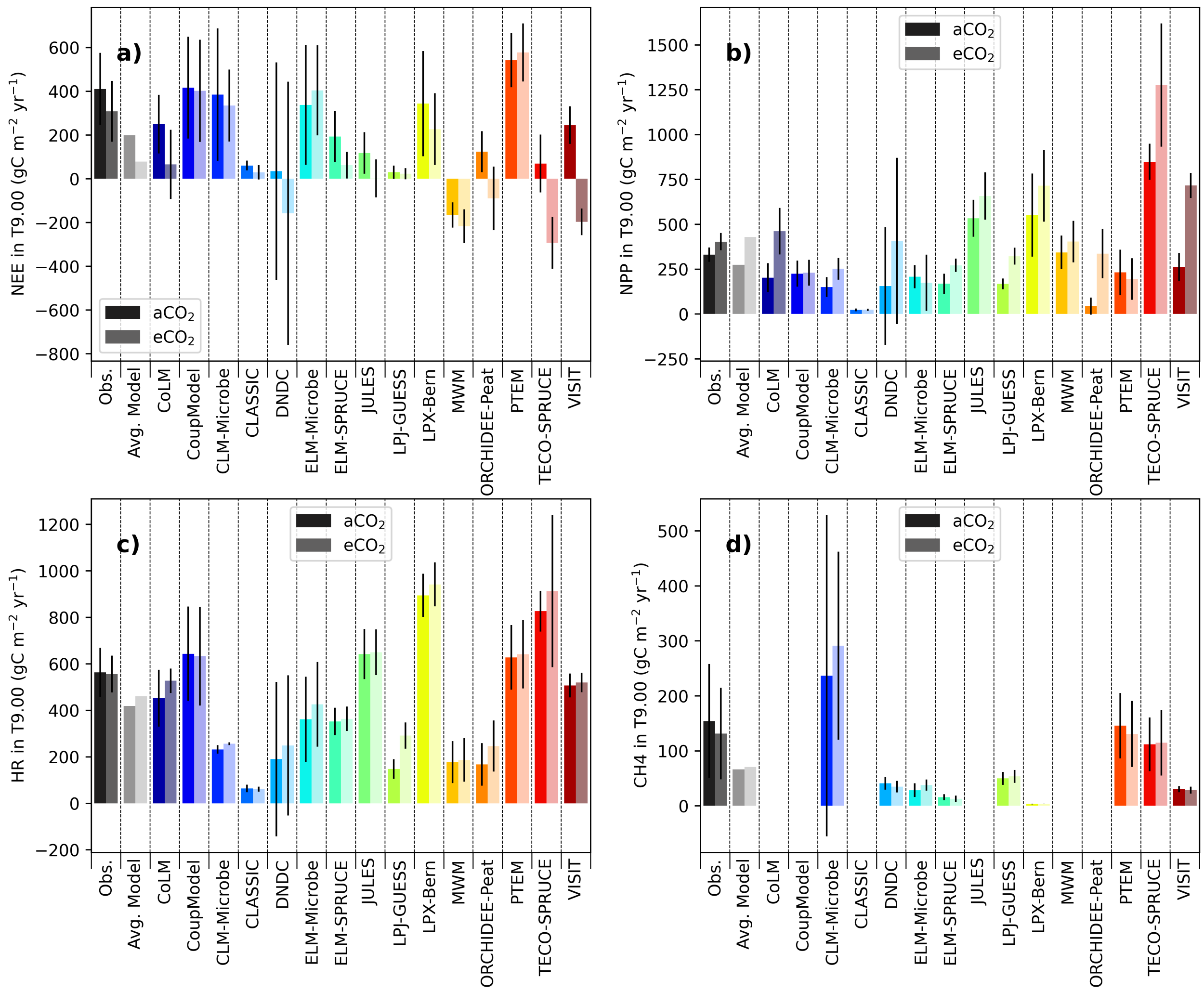

Fig. S5. Simulated a) NEE, b) NPP, c) HR and d) CH_4 compared with observed (Obs) values under the +9.00 °C warming treatment at aCO_2 and eCO_2 conditions. Bars represent multi-year means (2015-2021), and error bars denote interannual standard deviations of annual values. Note that NEE includes the carbon equivalent of CH_4 emissions to account for their contribution to changes in peat carbon stocks.

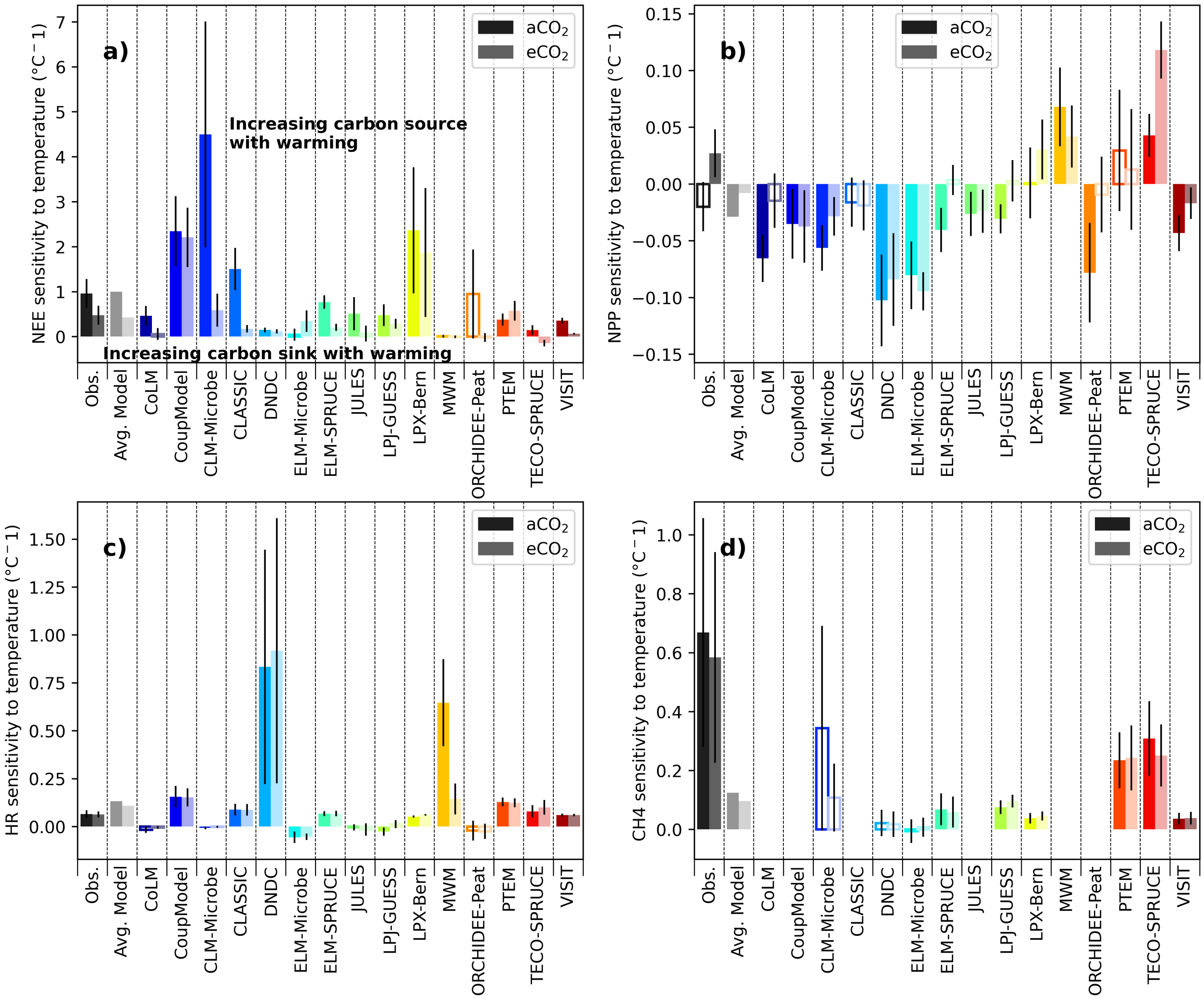

Fig. S6. Temperature sensitivities of a) NEE, b) NPP, c) HR, and d) CH4 normalized by the corresponding mean fluxes under the +0 °C treatment (Fig. 3) across the participating models compared with observed (Obs) values under both aCO_2 and eCO_2 conditions. This figure is identical to Fig. 4 except that the temperature sensitivities and their uncertainty intervals are divided by the absolute values of the corresponding multi-year mean fluxes under the +0 °C treatment (Fig. 3). Solid bars indicate statistically significant slopes ($p \leq 0.05$), whereas hollow bars indicate non-significant slopes.

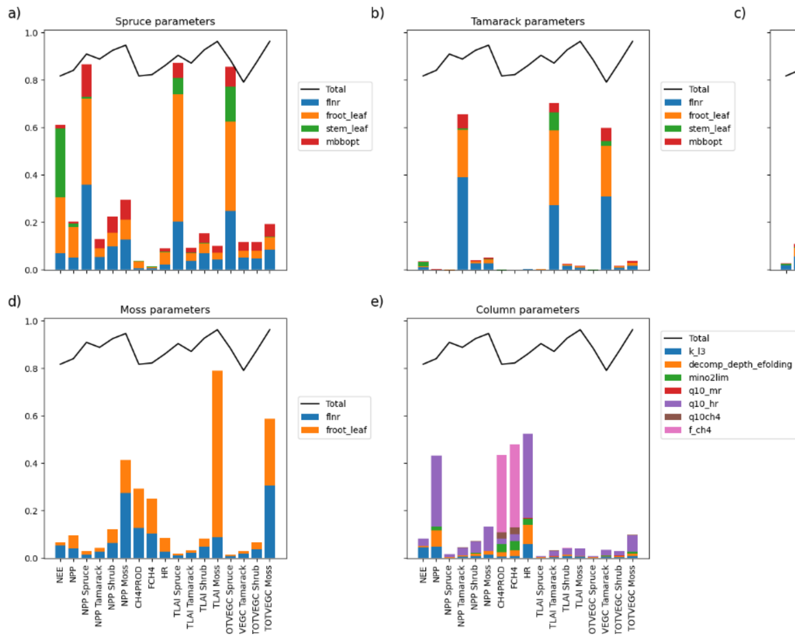

Fig. S7. Main effects of individual parameter perturbations in the ELM-SPRUCE sensitivity analysis for the +0 °C warming treatment under ambient CO_2 (aCO_2). Panels show the normalized sensitivity of simulated carbon fluxes to perturbations of (a) spruce parameters, (b) tamarack parameters, (c) shrub parameters, (d) Sphagnum moss parameters, and (e) soil (column) parameters. Stacked bars represent the relative contributions of individual parameters, and the black line indicates the total normalized sensitivity for each simulated variable.

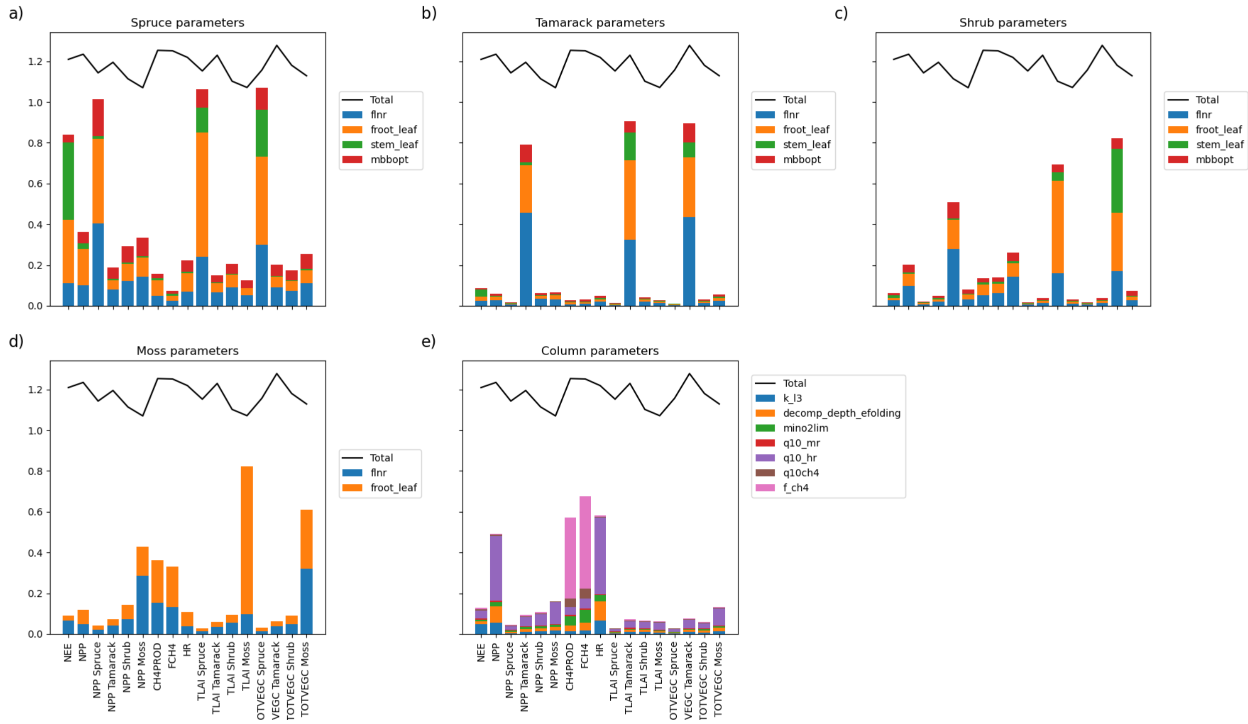

Fig. S8. Main effects of individual parameter perturbations in the ELM-SPRUCE sensitivity analysis for the +0 °C warming treatment under elevated CO_2 (eCO_2). Panels show the normalized sensitivity of simulated carbon fluxes to perturbations of (a) spruce parameters, (b) tamarack parameters, (c) shrub parameters, (d) *Sphagnum* moss parameters, and (e) soil (column) parameters. Stacked bars represent the relative contributions of individual parameters, and the black line indicates the total normalized sensitivity for each simulated variable.

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