https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Predicting soil-atmosphere CH_4 and CO_2 fluxes across several drained peatland forests with JSBACH-HIMMELI

Ellinoora Ekman[1], Xuefei Li[1], Antti Leppänen[2], Tuula Aalto[2], Jani Anttila[3], Jyrki Jauhiainen[3], Raija Laiho[3], Annalea Lohila[1, 2], Tiina Markkanen[2], Kari Minkkinen[4], Raisa Mäkipää[3], Paavo Ojanen[3, 4], Mikko Peltoniemi[3], Anuliina Putkinen[5,6], Maarit Raivonen[1]

[1]Institute for Atmospheric and Earth System Research (INAR) / Physics, Faculty of Science, University of Helsinki, Helsinki, Finland
[2]Finnish Meteorological Institute, Helsinki, Finland
[3]Natural Resources Institute Finland (LUKE), Helsinki, Finland
[4]Department of Forest Sciences, University of Helsinki, Helsinki, Finland
[5]Institute for Atmospheric and Earth System Research (INAR) / Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, Helsinki, Finland
[6]Environmental Soil Sciences, Department of Agricultural Sciences, University of Helsinki, Helsinki, Finland

Correspondence to: Ellinoora Ekman (ellinoora.ekman@helsinki.fi)

Abstract. Drainage and other land-use practices, including forestry, substantially influence soil carbon dynamics and associated greenhouse gas (GHG) exchange between boreal peatland soils and atmosphere. Besides the land-use, several site-specific environmental factors, such as water table level (WTL), soil temperature and vegetation regulate the peatland soil GHG balance. It is important to understand the interactions among these co-existing factors at site scale to improve estimates of soil GHG exchange at larger (e.g. regional) spatial scales. Process-based models are useful tools to make large scale estimations, but knowledge about how well the models can capture the variation among drained peatlands, and thus accurately simulate the soil GHG fluxes, are lacking. We simulated key environmental variables (water table level i.e. WTL and soil temperature) and soil–atmosphere methane (CH_4) and CO_2 (heterotrophic respiration) fluxes at six Finnish forestry-drained peatlands with a process-based JSBACH-HIMMELI model. Specifically, our focus was on evaluating the model performance and identifying the sources of uncertainty across multiple sites by using measurement data over several years from each site. The model predicted key environmental variables adequately well at each study site. In addition, we found that the there was more between-site variation in the prediction accuracy with the simulated CH_4 fluxes (NMRSE 1.02–9.25) than with the simulated CO_2 fluxes (NMRSE 0.62–1.24). Our study highlights WTL as the primary source of uncertainty in simulating the CH_4 fluxes. The sites characterized by consistently deep WTL exhibited substantially better agreement between the model and measurement with the soil–atmosphere CH_4 fluxes (RMSE 0.69–1.02 nmol m^{-2} s^{-1}), than sites characterized by higher WTL (RMSE 1.04–9.70 nmol m^{-2} s^{-1}). These discrepancies at high-WTL sites were associated with high anaerobic respiration peaks, which were enhanced by relatively thick modelled acrotelm (i.e. fast decomposing topsoil layer). Our results demonstrate that CH_4 parameterization has only a minor influence on modelled CH_4 fluxes, compared to WTL, but can nevertheless improve prediction accuracy, especially at sites characterized by high WTL.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

1 Introduction

Boreal peatlands have accumulated a significant amount of organic carbon over millennia, primarily due to the slow decomposition rate of organic matter under water-saturated conditions (Blodau, 2002). In addition to that, they are known for being a considerable natural source of atmospheric methane (CH_4), one of the major greenhouse gases (GHG) produced in the anaerobic decomposition process in the peat soils (IPCC, 2023). In the last centuries and decades, northern peatlands, especially in Europe, have been widely drained for different land-use purposes (UNEP, 2022), from which forestry has been common in the Nordics. Drainage exposes the peat above the WTL to oxygen, promoting aerobic decomposition of organic matter which, in turn, enhances carbon dioxide (CO_2) emissions from the peat to the atmosphere (Ojanen et al., 2013). Meanwhile, drainage reduces CH_4 emissions by inhibiting methanogens, i.e. microbes producing CH_4 under strictly anoxic environments, and still enables the activity of methanotrophs, i.e. microbes consuming CH_4 mainly in oxic conditions (Evans et al., 2021). Therefore, the soil–atmosphere CH_4 fluxes in these ecosystems are typically small and can range from emission to uptake (Jauhiainen et al., 2023).

The impacts of drainage on soil-atmosphere CO_2 and CH_4 fluxes have been assessed in the field conditions. It is well known that the mean water table level (WTL), deepened by the drainage activities, controls the fluxes of both CO_2 and CH_4 from drained peatland soils (Ojanen et al., 2010; Roulet et al., 1993). CH_4 production and oxidation potentials have been generally found to vary vertically in peat soils depending e.g. on the WTL, both being highest near to it (Kettunen et al., 1999; Yrjälä et al., 2011). Deep WTL decreases CH_4 production and the diversity of the methanogen communities in the peat (Yrjälä et al., 2011). Specifically at forestry-drained peatlands, tree stand volume is linked to the WTL (Sarkkola et al., 2010) through evapotranspiration: high stand volume means high evapotranspiration and deepening of the WTL (Leppä et al., 2020). In addition to WTL, soil nutrient level is an important driver in the soil CO_2 balance in these ecosystems, with more fertile soils often acting as net sources of CO_2, whereas more nutrient-poor soils may stay as sinks (Ojanen et al., 2013). Furthermore, other environmental factors, such as temperature and ground vegetation composition, simultaneously impact on the soil GHG balance (Ojanen et al., 2010), making it challenging to separate the impacts of these co-existing factors.

In addition to field studies, process-based modelling is another approach to study the soil greenhouse gas (GHG) fluxes at drained peatlands. Several models have been developed and used to simulate co-existing processes in peatlands, including biophysical and biogeochemical processes, such as cycling of water and carbon across a range of temporal scales and site-specific conditions (Mozafari et al., 2023). Recently, some land surface models containing peatland processes have been implemented, at both site and regional scales, to investigate greenhouse gas fluxes in northern peatlands, but these studies have been mainly focusing on simulating CO_2 and CH_4 fluxes (with high CH_4 emissions) from pristine peatlands (Gao et al., 2025; Kallingal et al., 2025; Qiu et al., 2018). Attempts to model soil GHG fluxes from drained peatlands, to better understand the effect of several simultaneous factors (i.e. environmental conditions and different management types) on the soil GHG fluxes at site scale, have been so far scarce. Liu et al. (2026) developed a new parameterization for simulating peat drainage in ORCHIDEE-PEAT model, but they compared the simulation results with meta-analysis that used only ecosystem-level CO_2

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

and CH_4 fluxes averaged over all sites. Single-site simulations with drained peatland forests have been recently conducted by Shahriyer et al. (2026) and Li et al. (2024), who both calibrated their models to fit to a single site, and focusing on comparing soil GHG fluxes between different harvesting intensities.

To our knowledge, no process-based modelling studies have validated simulated soil –atmosphere CH_4 and CO_2 fluxes against multi-year measurements from multiple drained peatland forest sites. One major challenge is that the site-specific environmental variability drives the fluxes that these models with generic parameterizations cannot accurately simulate. However, it would be essential to validate the models against several sites, to be able to understand the level of accuracy of the simulated fluxes, and further, to be able to simulate fluxes over larger areas. Moreover, process-based modelling studies focusing on soil–atmosphere CH_4 fluxes in drained peatlands forests remain scarce, despite the fact that these ecosystems can function both as methane sources and sinks. To fill this gap, we applied land surface model JSBACH (Jena Scheme for Biosphere–Atmosphere Coupling in Hamburg) (Reick et al., 2021) together with a peatland CH_4 model, HIMMELI (HelsinkI Model of MEthane buiLd-up and emission) (Raivonen et al., 2017) to simulate the soil CH_4 and CO_2 fluxes from six boreal drained peatland forests located in Finland. We used the model version of JSBACH-HIMMELI that has been recently improved by Li et al. (2024) to suit better for the special characteristics of drained peatland forests.

Our aim is to evaluate model performance and improve understanding of the sources of uncertainty in simulating soil–atmosphere CH_4 and CO_2 fluxes of drained peatland forests using the JSBACH-HIMMELI model across multiple sites over several years. Our approach includes, first, an evaluation of model performance through investigating the effects of site-level WTL fitting and a common set of CH_4 parameter values at all study sites. To achieve this, we use in situ multi-year measurement data of environmental variables and soil–atmosphere fluxes. Second, we improve understanding of the main sources of uncertainty by examining model bias in simulated soil GHG fluxes with WTL as the primary source of uncertainty, and by evaluating the potential of the CH_4 parameterization to improve the prediction of the simulated CH_4 fluxes. We address the following research questions: 1) How well JSBACH-HIMMELI can predict the temporal and across-site variation of WTL, soil temperature and the consequent soil CH_4 and CO_2 fluxes in multiple peatland forests? and 2) How can the discrepancies between modelled and observed fluxes be explained and reduced?

2 Materials and methods

2.1 Description of the sites

Our study sites included six boreal drained peatland forests in Finland (Fig. 1), representing various peatland forest types (Table 1). Some of the sites were divided in experimental study plots representing different harvesting intensities (Laurila et al., 2021). However, in our study we used data only from the control plots, i.e. no recent harvesting has been done on them. Based on vegetation surveys, the coverage of aerenchymatous plants in these study sites was 0–1.5 %. Since WTL is an important factor controlling the soil GHG balance, we used a division in two groups in our site simulations: deep-WTL group, including Lettosuo, Kalevansuo and Paroninkorpi sites, and high WTL group, including Sinilammenneva, Kivalo and

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Rouvanlehto sites. In the deep-WTL group, the mean measured WTL was around -0.3 m and in the high-WTL group it was deeper than -0.4 m (Table 1).

Table 1. Information about study sites. Mean air temperature and precipitation for 1991–2020 for each site were extracted from the closest weather stations of the Finnish meteorological Institute open data service: https://www.ilmatieteenlaitos.fi/.

Site	Kalevansuo	Kivalo	Lettosuo	Paroninkorpi	Rouvanlehto	Sinilammenneva
Coordinates	N 60°38, E 24°21	N 66°20′, E 26°40′	N 60°38, E 23°57	N 61°06’, E 24°45’	N 62°32’, 28°35’E	N 61°47’46°, E 24°17’7°
Peatland forest type (Laine et al., 2012)	dwarf shrub	herb-rich	*Vaccinium myrtillus*	herb-rich	herb-rich	*Vaccinium vitis-idaea*
Nutrient level	poor	rich	rich	rich	rich	poor
Dominant tree species	*Pinus sylvestris*	*Picea abies*	*Pinus sylvestris, Picea abies*	*Picea abies*	*Picea abies*	*Pinus sylvestris*
Basal area (m^{-2} ha^{-1})	17	30	30	25.5	21	35
Data period	2004–2005	2016–2018	2020–2021	2017–2021	2018–2019	2018–2020
Peat layer thickness (m)	2.2	< 1.0	2.0	> 1.5	> 1.0	> 1.0
Mean (±sd) WTL (m)	-0.42 ± 0.11	-0.3 ± 0.11	-0.53 ± 0.13	-0.64 ± 0.16	-0.31 ± 0.13	-0.31 ± 0.1
Mean annual air temperature (°C) (1991–2020)	5.2	1.0	5.2	4.7	4.4	4.1
Mean annual precipitation (mm) (1991–2020)	656	555	621	639	630	690
Reference	(Lohila et al., 2011; Minkkinen et al., 2018)	(Korrensalo et al., 2026)	(Korkiakoski et al., 2019, 2023)	(Korrensalo et al., 2026; Laurila et al., 2021)	(Korrensalo et al., 2026; Laurila et al., 2021)	(Korrensalo et al., 2026; Laurila et al., 2021)

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

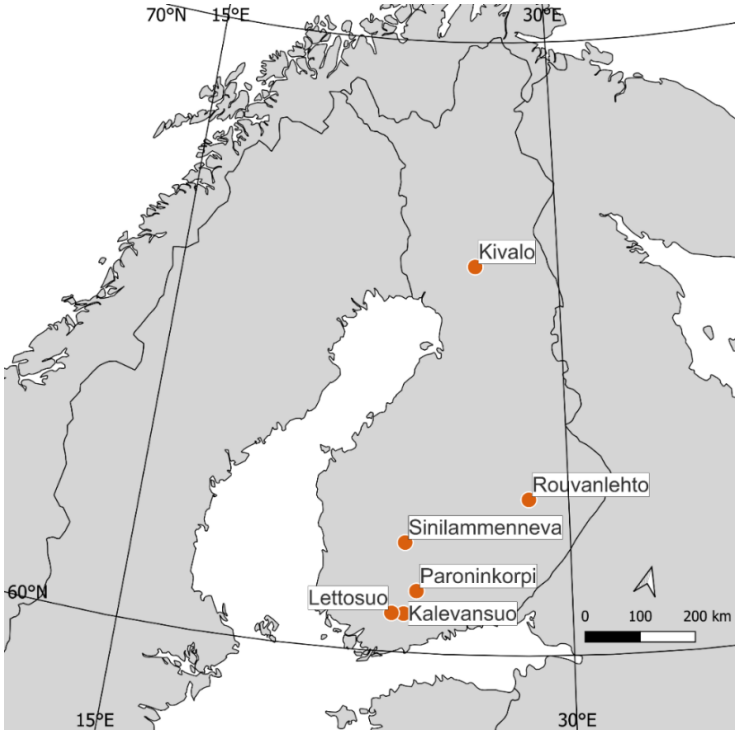


Figure 1. The location of the study sites in Finland. Background map sources: Esri, Garmin, and U.S. Central Intelligence Agency (The World Factbook) | Powered by Esri. For more information on this map, visit: https://hub.arcgis.com/datasets/esri::world-countries-generalized/about (last access: 11.11.2026). Visualised in QGIS v 3.36.2.

2.2 Data

2.2.1 Measurement data

2.2.1.1. Soil–atmosphere fluxes

Soil–atmosphere CO_2 and CH_4 flux data from the study sites was measured with the closed-chamber technique. CO_2 fluxes were measured as heterotrophic respiration from sample plots where roots were excluded by trenching, i.e. the flux represents respiration resulting from the decomposition of organic matter (Korrensalo et al., 2026; Minkkinen et al., 2018). CH_4 fluxes were measured from undisturbed sample plots containing ground vegetation, litter and roots (Laurila et al., 2021; Lohila et al., 2011). Chamber measurement plots were distributed around the study sites, and all measurements were conducted in the strips between the drainage ditches. Depending on the site, 85–100 % of the CH_4 flux measurements and 92–100 % of the CO_2 flux measurements were conducted during the snow-free period (April–November). Soil CO_2 and CH_4 fluxes were derived from the assumption of a linear change in chamber headspace gas concentration over the closure period, and their estimates were adjusted for chamber air temperature (Korrensalo et al., 2026; Lohila et al., 2011). For one site (Kivalo), there was no data available for heterotrophic respiration. For each peatland site, daily mean fluxes were calculated by averaging all measurements collected across the experimental study plots within the site on a given day.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

2.2.1.2 Environmental data

WTL measurement setups at Lettosuo, Rouvanlehto, Sinilammenneva and Paroninkorpi sites has been described previously by Korrensalo et al. (2026), while the setup at Kalevansuo site has been described by Lohila et al. (2011). WTL measurement data used in this study was continuous logger data, except the data from Kivalo site, which was measured near GHG monitoring plots during the GHG data collection. There was no continuous WTL data available from this site due to technical problems. Soil temperature at 5 cm below soil surface was measured with temperature loggers (i-Button DS1921G, Maxim Integrated Products) (Korrensalo et al., 2026; Minkkinen et al., 2018). Both WTL and soil temperature data were collected every 1–3 hours, depending on the site and plot, and averaged to daily values for this study.

2.2.2 Meteorological forcing data

In the JSBACH simulations, we used ERA5-Land reanalysis data as the meteorological forcing data (Muñoz-Sabater et al., 2021). This data included precipitation, relative humidity, wind speed, air temperature, longwave radiation downwards and shortwave radiation downwards. Global annual means were used for CO_2 concentration. We also extracted precipitation and air temperature data from the closest weather stations for each study site and measurement period (Table A1) to compare it with ERA5-Land data. This data is openly available in https://www.ilmatieteenlaitos.fi/havaintojen-lataus.

2.3 Models

JSBACH is the land component of the Earth system model of Max Plank Institute (MPI-ESM), developed to simulate the terrestrial cycling of carbon, energy and water (Reick et al., 2013, 2021). The current JSBACH used a multilayer soil hydrological model (Hagemann and Stacke, 2015) and YASSO as the soil carbon module (Goll et al., 2015; Tuomi et al., 2009). HIMMELI is a process-based model designed primarily to be used as a module for CH_4 exchange in peatlands (Raivonen et al., 2017). Since O_2 is an important factor for CH_4 production and oxidation, HIMMELI simulates processes affecting it, such as aerobic soil respiration and CH_4 oxidation. Consequently, simulation of peat CO_2 emission in HIMMELI is interconnected with the simulation of CH_4 exchange. Our modelling framework using JSBACH and HIMMELI (Fig. 2) follows the prior work by Li et al. (2024). In this study, JSBACH was driven with meteorological forcing at site level for the six peatland sites. It produced the necessary inputs for HIMMELI which was run separately as a standalone model to simulate the final peat CH_4 and CO_2 fluxes. A more detailed description of how forestry-drained peatland was implemented in the models is available in Li et al. (2024) and here we focus on what was changed and developed in the current work.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

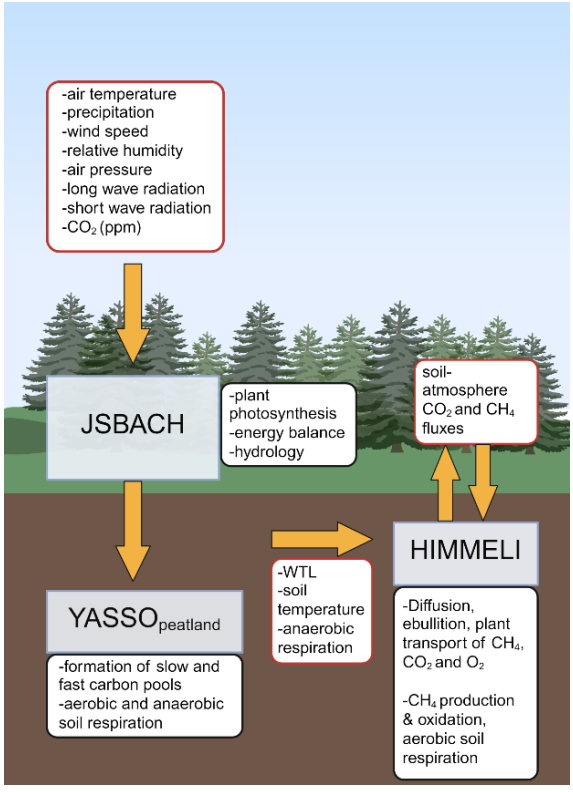


Figure 2. JSBACH-HIMMELI setup in this study. Created in BioRender. Ekman, E. (2026) https://BioRender.com/ wxh9afx

2.3.1 Vegetation and LAI in JSBACH

In JSBACH, the land surface within each grid cell is divided into tiles, each representing a specific land cover type. In this study, land cover type is described using plant functional types (PFTs). Each PFT is associated with parameters describing, for example, its photosynthesis, phenology and growth properties. In our site simulations, we used extratropical evergreen forest as the sole PFT in the whole grid cell, since conifers were the dominant tree species at all our sites (Table 1). The growth of vegetation is limited in the model by the phenological parameter LAI_{max}, i.e., maximum leaf area index of the PFT.

We did not have the exact information about the development of LAI at our study sites during the measurement data periods. However, we used the measured basal areas (Table 1) to define the LAI_{max} values used in the model, since LAI has been found to increase nonlinearly with increasing basal area in coniferous forests (Appiah Mensah et al., 2020). Besides, in the previous study by Li et al. (2024), a value 3.5 was used as LAI_{max} to simulate Lettosuo control site (i.e. no harvesting), and in Majasalmi et al. (2018) study, the LAI_{max} values simulated with JSBACH over forests in Finland ranged between 2 and 4. By using this information, and the basal areas, which ranged between 17 and 35 m^{-2} ha^{-1} in our study sites (Table 1), we decided to use value 3 as LAI_{max} at sites with basal area between 17 and 21 m^2 ha^{-1} (Kalevansuo, Rouvanlehto), and value 3.5 at sites with basal area between 25.5 and 35 m^2 ha^{-1} (Paroninkorpi, Sinilammenneva, Lettosuo, Kivalo).

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

2.3.2. Simulation of peat carbon with YASSO

The soil carbon model YASSO simulates accumulation of litter to different soil carbon pools (soluble in acid, water, and ethanol, a non-soluble pool and the humus pool) and their decomposition. The first four pools, in the topsoil, decompose more rapidly, while the more slowly decomposing humus lies beneath them. YASSO was originally developed for mineral soils (Thum et al., 2020; Tuomi et al., 2009), utilizing observational data from, for example, litter bag experiments, and is thus driven with 15 days mean air temperature and precipitation. We used a version of YASSO that has been specially developed for peatlands, called $YASSO_{peatland}$. The JSBACH version coupled with $YASSO_{peatland}$ was implemented by (Kleinen et al., 2020). The full description of $YASSO_{peatland}$ and model parameterization used in our study can be found in Li et al. (2024). Briefly, in our model, the WTL divides the soil column into anoxic and oxic layers. Decomposition is anoxic below the WTL, with the decomposition rate reduced by a factor of 0.35 compared to oxic conditions. In addition, the original humus pool has been replaced by a catotelm carbon pool containing carbon from the lower part of the peat column, where the decomposition rate is further reduced. The upper part, acrotelm, consists of the faster decomposing carbon pools both above- and belowground.

2.3.3 Simulation of WTL in JSBACH

The WTL of each site was simulated using the approach by Li et al. (2024), in which the variation of the WTL is derived from soil moisture but two scaling parameters adjust its overall level and the range of variation. In this approach, the simulated transpiration of the tree stand affects the WTL. In contrast, in the original JSBACH representation of WTL for pristine peatlands (e.g., in Petrescu et al., 2023), WTL is controlled by potential (equilibrium) evapotranspiration. Li et al. (2024) determined the scaling parameter values by fitting the model into observational WTL data from different harvesting intensity study plots of the Lettosuo site from years 2016–2019. In the current work, we first tested running the WTL model for all our six sites with the same scaling parameter values as which Li et al. (2024) used for their control (i.e. non-harvested) study plot. From now on, this option is called *default.* Next, we found the most optimal scaling parameter values for each peatland site individually by fitting the WTL model to the WTL data measured at the site (Table B2). This option is called *site-level fitted.*

2.3.4 HIMMELI

HIMMELI simulates the build-up and transport of CH_4, CO_2 and O_2 in peatland soils (Raivonen et al., 2017). The model structure consists of a one-dimensional vertical soil column, which is divided into layers. The processes in HIMMELI include microbial CH_4 production and oxidation as well as aerobic respiration and transport paths for CH_4, O_2 and CO_2 including ebullition, diffusion (in water- and air-filled soil) and plant transport via aerenchymatous plants. Simultaneously, the model keeps track on CH_4, O_2 and CO_2 concentrations in the soil layers. The model uses WTL, LAI of aerenchymatous plants, soil temperature profile and the rate of anaerobic soil respiration as input and, therefore, runs only in combination with another

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

model that provides these. As output, HIMMELI produces the fluxes of CH_4, CO_2 and O_2 between the atmosphere and the soil via different transport paths. The CO_2 flux from HIMMELI represents heterotrophic soil respiration.

Originally HIMMELI was developed for pristine peatlands (Raivonen et al., 2017), but we applied the model version v200 modified by Li et al. (2024) which is better suited for predicting both CH_4 uptake and emissions from drained peatlands. It differs from the original version v.1.0 in how the concentrations of compounds are treated when WTL drops (which in the model means that the soil layer dries). The original version allowed for artificial steep concentration gradients to develop between adjacent air-filled peat layers, but in HIMMELI v.200, this has been suppressed. This modification reduced high CH_4 emission peaks following WTL drop (Li et al., 2024). As a new development of HIMMELI in the present work, we implemented the possibility to use vertically varying values of two parameters: the proportion of anaerobic respiration becoming CH_4 without the presence of oxygen (*fm*, dimensionless) and CH_4 oxidation potential at 10 °C (V_{o10}, mol m^{-3} s^{-1}).

2.4 Model runs

2.4.1 JSBACH runs

The initial states of soil carbon pools for each site were produced in spin-up runs. Peat was accumulated by running only the soil carbon processes of JSBACH, which requires as input just a few variables, among others, net primary production rate (NPP), LAI and WTL. These spin-up runs were driven with 31 years (1990–2021) of meteorological forcing data. The resulting 31 years of input data for the soil carbon spin-up were looped until reaching the correct peat thickness at each site (Table 1, Table B1). In these runs we used C3 grass as the PFT since we assumed for simplicity that prior to drainage, the peatland sites have been treeless or at least less densely forested than after the drainage. In addition, for consistency, we kept the WTL constant at the ground surface level.

The resulted carbon pools were used to implement the final JSBACH runs at each site, by using the site-specific meteorological forcing data (1990–2021), correct WTL (*default* or *site-level fitted*), and conifers as the PFT. By starting the final simulations from 1990 were found enough to stabilize the initial rapid decomposition of the acrotelm (i.e. fast decomposing topsoil carbon pools) (Fig. B1). We also tested with one peatland site, whether extending the simulation by looping the forcing data would significantly change the acrotelm thickness, but the change remained small. Since taking into account the site-specific history with, e.g. the drainage year, ditch maintenance and canopy development was not possible to implement realistically, we considered it reasonable to use the simulation data from the first 1990–2021 loop. Following the final JSBACH runs, we extracted input data required by HIMMELI (Fig. 2) for the years with available observations at each study site (Table 1). The simulated total peat depths of those years corresponded to what was known about the peat depths of the sites.

2.4.2 HIMMELI runs

We ran HIMMELI, driven by the site-specific input data produced in the JSBACH runs, as in Li et al. (2024). The vertical soil layers in HIMMELI followed the same (logarithmic) layers as used in JSBACH: 0–6 cm, 6–19 cm, 19–45 cm, 45–97 cm and

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

97–200 cm below ground. The soil carbon model YASSO only divided the soil layer into the acrotelm and catotelm, but the soil temperature output from JSBACH was layered. HIMMELI was first spun up by cycling the input data 60 times to make sure the equilibrium of the gas concentrations was reached, and the final CH_4 and CO_2 fluxes, used in this study to compare with the measurements, were extracted from the final run. JSBACH also simulates the soil CO_2 flux from both aerobic and anaerobic soil respiration, but it does not contain the CO_2 originating from the oxidation of CH_4.

The initial parameter values of HIMMELI, called *baseline* from here on, were the same as in Li et al. (2024) (Table 2). In addition to the *baseline*, we ran several alternative versions of *fm* and V_{o10} to understand how the model performance could be improved, depending on the general WTL of the site (Table 2). It has been found that drainage suppresses CH_4 production in the peat and thus also reduces the potential CH_4 oxidation rate (Jaatinen et al., 2005; Juottonen et al., 2012). Therefore, we reduced the V_{o10} parameter value at deep-WTL sites, based on the assumption that a deeper WTL would suppress the CH_4 oxidation more strongly than at the high-WTL sites. For the high-WTL sites, the *fm* parameter was reduced following the findings of an earlier sensitivity analysis using the same model setup in a drained peatland forest, where high water table conditions led to pronounced peaks in simulated anaerobic respiration (Li et al., 2024), which further increases CH_4 production in the model. In these alternative versions we used both reducing values of *fm* and V_{o10} throughout the soil layers (reduced), and reducing their values only in certain layers (profile), because previous studies at drained peatlands have shown both CH_4 production and oxidation potentials to vary along the peat depth (Galand et al., 2005; Jaatinen et al., 2005). The values of CH_4 oxidation potentials used in these versions were based on two unpublished studies (Ekman et al.; Putkinen et al.) in which the measured CH_4 oxidation potentials from two Finnish forestry-drained peatlands ranged between 1.6×10^{-9} and 1.5×10^{-5} mol m^{-3} s^{-1}, being highest close to the surface and close to the WTL. Therefore, we assigned the highest values in the V_{o10} profile to the topsoil, and to the soil layer closest to the average WTL of the deep-WTL group. Similarly, to the *fm*-profile version we set the highest value close to the mean WTL of the high-WTL group sites, as the WTL and right below it has been shown to be the most active zone for CH_4 production (Kettunen et al., 1999; Peltoniemi et al., 2023).

Before the actual alternative CH_4 parameter runs, we performed a sensitivity test to understand how the values of *fm* and V_{o10} affect the modelled CH_4 fluxes. We tested this with two sites: one high-WTL site (Kivalo) and one deep-WTL site (Paroninkorpi). For *fm*, we chose values from the lower end of the range (0–0.3) reported by Nilsson and Öquist (2009) because much lower CH_4 production potentials have been found in drained peatlands compared to pristine peatlands (Urbanová and Bárta, 2020). For V_{o10}, we tested a percentual change in the parameter value from the initial *baseline* value. The range of the parameter values used was $6 \times 10^{-6} – 2.4 \times 10^{-5}$ mol m^{-3} s^{-1}. We also included the profile versions (Table 2) in the sensitivity test. Parameter values for the actual alternative HIMMELI runs were based on the same principles.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Table 2. HIMMELI CH_4 parameter value modifications used in this study. The values of *fm* and V_{o10} depth profile versions are given here from the top to the bottom of the peat column. Profile peat layer depths (below ground) are given after the parameter value.

parameter	unit	*baseline*	reduced *fm*	*fm* profile	reduced V_{o10}	V_{o10} profile
fm	-	0.06	0.02	0 (0–6 cm), 0.02 (6–19 cm), 0.06 (19–45 cm), 0.02 (45–97 cm), 0 (97–200 cm)	0.06	0.06
V_{O10}	mol m^{-3} s^{-1}	1.5×10^{-5}	1.5×10^{-5}	1.5×10^{-5}	6×10^{-6}	1.5×10^{-5} (0–6 cm), 6×10^{-6} (6–19 cm), 6×10^{-6} (19–45 cm), 1.5×10^{-5} (45–97 cm), 6×10^{-6} (97–200 cm)

2.5 Evaluating the model performance

We used Root Mean Square Error (RMSE) and Pearson's correlation coefficient (r) to quantify the discrepancies between model prediction and measurement of WTL and soil GHG fluxes. We also calculated the normalized RMSE (NRMSE) by dividing the RMSE by the standard deviation of the measured values, allowing comparison of the discrepancies between CH_4 and CO_2 fluxes. Measured soil flux data consisted of a rather low number of daily observations over several years. To compare measurements and model predictions more reliably with each other, we calculated modelled values as moving averages of ±5 days (around the measurement day), instead of using only one modelled value of the specific day. We also used moving averages similarly for the WTL data from the Kivalo site. All statistical analyses were performed using R version 4.4.2 (R Core Team, 2024).

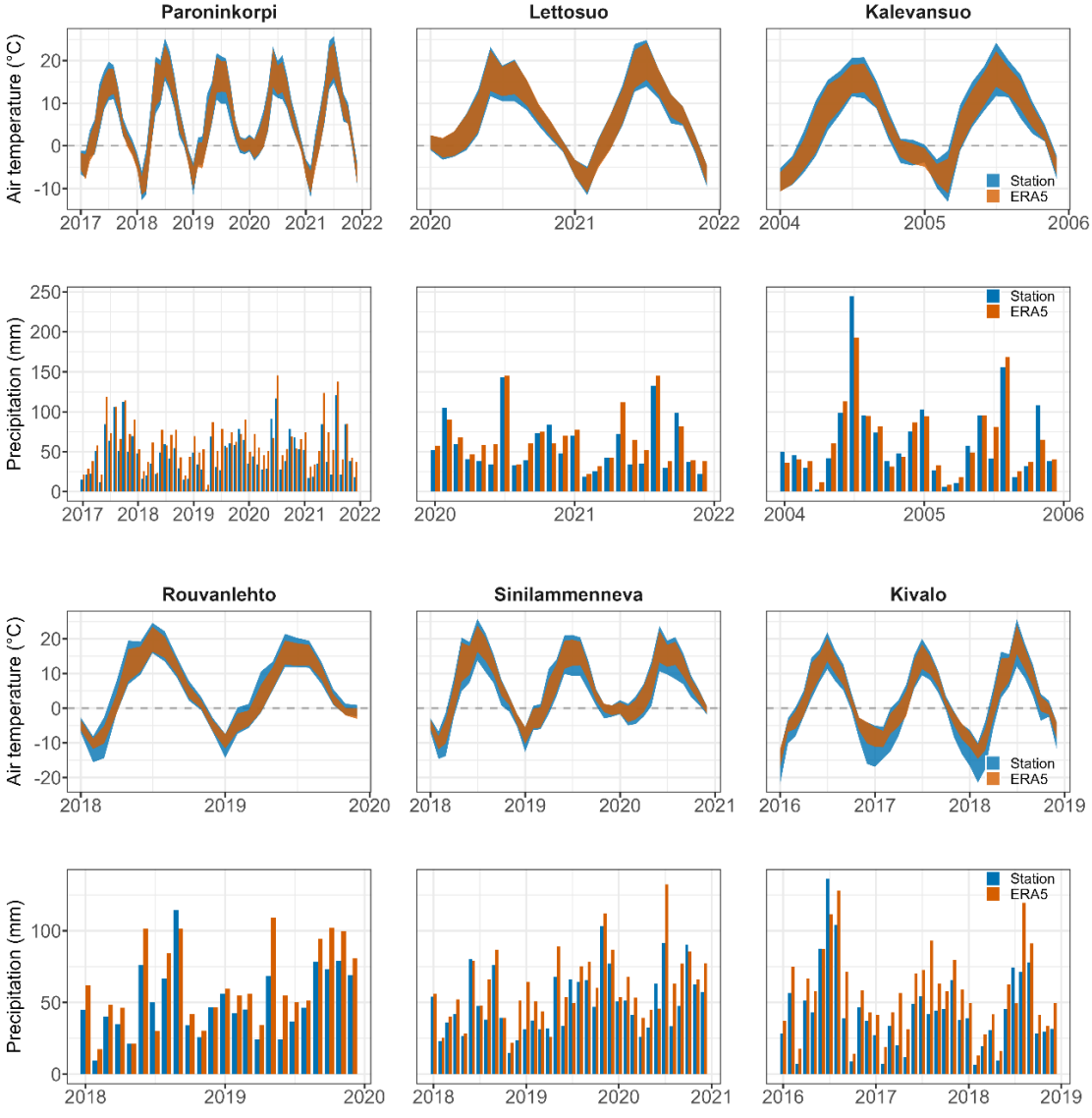
3 Results

3.1. Simulation of environmental drivers

To validate the forcing meteorological data used in JSBACH simulations across sites, we compared precipitation and air temperature data from ERA5-Land with the weather station data from each study site (Fig. 3, Table A1). The comparison showed a good agreement in air temperatures at the study sites (Fig. 3). Some differences occurred in the minimum temperatures, especially during the winter months at the Northern Kivalo site. The good agreement between observed and simulated air temperatures was also reflected in the simulated soil temperatures as the model adequately reproduced both their range and general level across all study sites (Fig. 4). ERA5-Land and weather stations gave similar yearly distribution of

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

precipitation (Fig. 3). However, ERA5-Land had higher accumulated monthly precipitation values than the station data, at some sites.



285

Figure 3. ERA5-land (used in the JSBACH-simulations) vs weather station data at each peatland forest site. Temperature range shown between minimum and maximum temperatures, averaged from daily values to monthly values. Precipitation values are calculated as monthly accumulated sums from the daily values.

290 To simulate the WTL in JSBACH we applied *site-level fitted* option and *default* option (i.e. common WTL parameter values, based on data from the Lettosuo site, used at all sites, Table B2). It was shown that the *site-level fitted* option reduced

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

significantly the discrepancy between modelled and measured WTL compared to the *default* option. The *default* option resulted in significantly deeper WTL at all sites than the *site-level fitted* option (Fig. B2). The mean difference between modelled and measured WTL was 0.13–0.46 m with the *default* option, whereas it was reduced to 0–0.02 m when the *site-level fitted* option was applied. When fitting the WTL to site-level, the correlation coefficients between the fitted modelled and measured WTL were between 0.50 and 0.91, depending on the site (Table 3). Kivalo had the lowest coefficient, and the smallest data coverage (no continuous data available). The RMSE values were between 0.05–0.11 m (Table 3). There was generally less variation (lower sd) in the modelled than measured WTL between the sites. The model did not capture some of the extremely deep drops in WTL (Lettosuo, Rouvanlehto) (Fig. 4). Yet, the model overestimated some high WTL values at Kalevansuo, Paroninkorpi and Rouvanlehto sites (Fig. 4).

Table 3. Mean±standard deviation of measured and modelled WTL (simulated with site-level fitted parameters), Pearson correlation coefficient (r) for measured versus modelled WTL, and root mean square error (RMSE) of WTL. The modelled values for Kivalo have been calculated as ± 5 day moving averages because of the low number of WTL measurements.

Site	Mean ± sd (m)		r	RMSE (m)
	modelled	measured		
Paroninkorpi	-0.64 ± 0.11	-0.64 ± 0.16	0.69	0.11
Lettosuo	-0.51 ± 0.06	-0.53 ±0.13	0.91	0.05
Kalevansuo	-0.42 ± 0.1	-0.42 ± 0.11	0.84	0.06
Rouvanlehto	-0.32 ± 0.08	-0.31 ± 0.13	0.61	0.10
Sinilammenneva	-0.31 ± 0.06	-0.31 ± 0.1	0.60	0.08
Kivalo	-0.3 ± 0.05	-0.3 ± 0.11	0.50	0.09

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

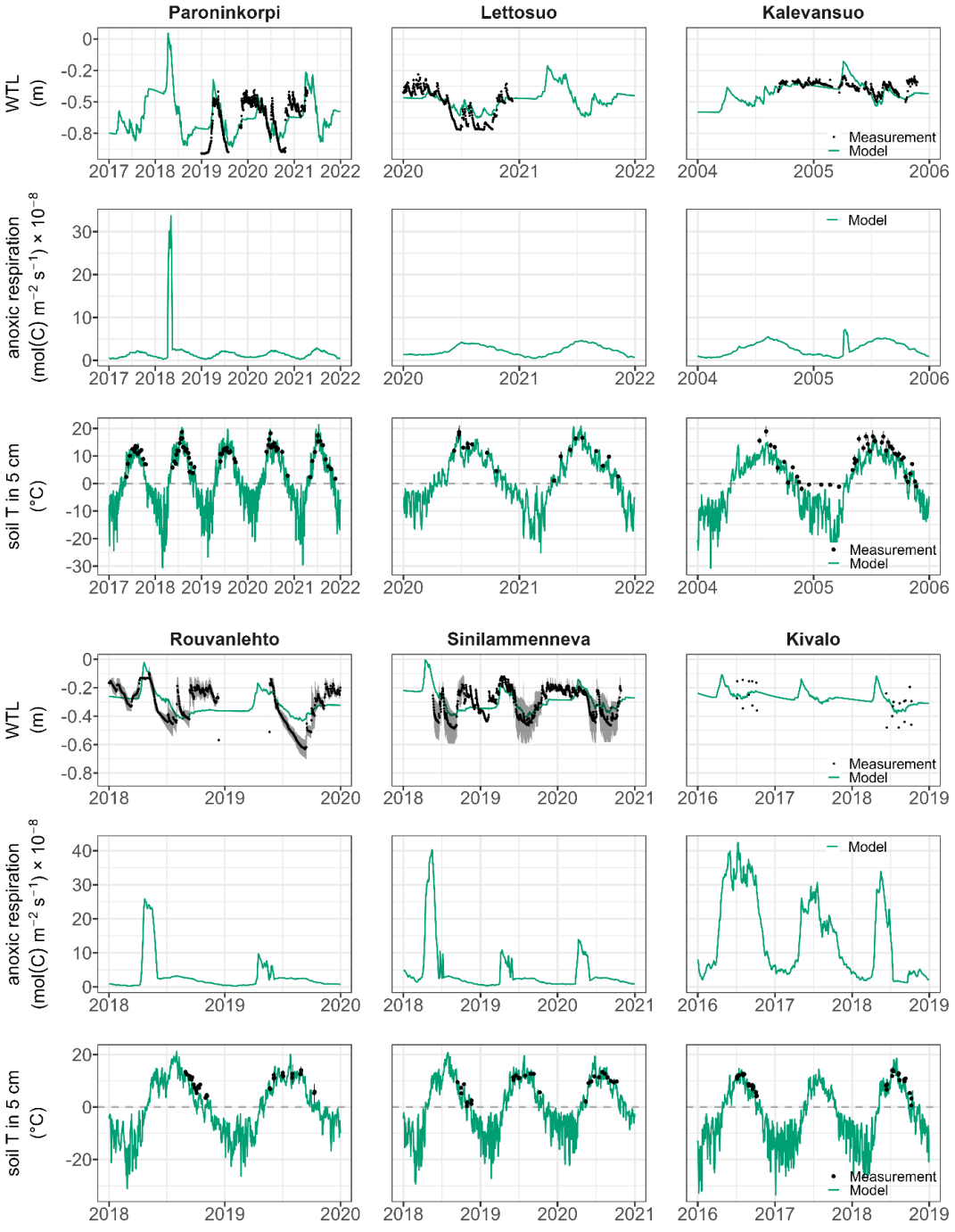


Figure 4. WTL, anoxic soil respiration and soil T in 5 cm below ground. Error bars of the measured values show standard deviation of the daily soil temperature and grey area indicates the range of the daily measured WTL.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

3.2. Simulation of CH_4 and CO_2 fluxes with *baseline* HIMMELI

On average, all study sites acted as CH_4 sinks with measured mean values varying between -0.25±0.11 and -2.16±0.94 nmol m^{-2} s^{-1} (Table 4, Fig. 5). When applying the *baseline* version of HIMMELI at all study sites, the CH_4 sink was consistently overestimated at two sites (Lettosuo and Kalevansuo) (Fig. 5). At one site (Paroninkorpi), the modelled CH_4 sink was clearly underestimated in 2019 and 2021. On the other hand, the model consistently underestimated CH_4 sink at Rouvanlehto and predicted occasionally high CH_4 emissions at both Rouvanlehto and Kivalo sites. The Pearson correlation coefficients varied greatly, from -0.22 to 0.70 among all study sites. The discrepancies between the modelled and measured CH_4 fluxes were generally higher than those for CO_2 fluxes. The normalized RMSE (NRMSE) values varied between 1.02 and 9.25 for CH_4 fluxes (Table 4).

Table 4. Modelled and measured mean±standard deviation of the soil CH_4 and CO_2 (= heterotrophic respiration) fluxes, and Pearson correlation coefficient (r), Root Mean Square Error (RMSE) and Normalized Root Mean Square Error (NRMSE, dimensionless) between modelled and measured fluxes. Modelled fluxes calculated here as ±5 day moving averages.

Site	CH_4 flux (nmol m^{-2} s^{-1})					CO_2 flux (µmol m^{-2} s^{-1})				
	modelled mean±sd	measured mean±sd	r	RMSE	NMRSE	modelled mean±sd	measured mean±sd	r	RMSE	NMRSE
Paroninkorpi	-1.52±0.42	-2.10±0.99	0.53	1.02	1.02	2.41±0.86	1.73±0.85	0.65	0.98	1.15
Sinilammenneva	-0.54±0.93	-0.64±0.53	0.05	1.04	1.95	1.00±0.40	1.20±0.68	0.52	0.61	0.89
Lettosuo	-1.33±0.39	-0.42±0.13	0.70	0.96	7.29	1.84±0.83	1.85±1.00	0.77	0.62	0.62
Rouvanlehto	-0.32±1.94	-2.16±0.94	-0.22	2.95	3.14	1.23±0.57	3.46±2.49	0.67	3.07	1.24
Kalevansuo	-0.87±0.34	-0.25±0.11	0.39	0.69	6.13	1.13±0.54	1.61±0.98	0.77	0.82	0.84
Kivalo	6.07±7.42	-0.40±1.05	0.14	9.70	9.25	-	-	-	-	-

The modelled and measured soil–atmosphere CO_2 fluxes (i.e. heterotrophic respiration) agreed generally better compared to the CH_4 fluxes. Measured daily mean CO_2 fluxes varied between 1.10±0.71 and 3.16±2.27 µmol m^{-2} s^{-1}). The model captured the seasonal pattern successfully (Fig. 5). However, there was a clear mismatch at Kalevansuo site where the modelled CO_2 fluxes were underestimated. Also, at Rouvanlehto site, the modelled CO_2 fluxes were clearly underestimated in 2018. The Pearson correlation coefficients for CO_2 fluxes varied 0.52–0.77 among the sites, indicating rather good agreement between model and measurement (Table 4). The normalized RMSE (NRMSE) values varied between 0.62 and 1.24 for CO_2 fluxes, ranging much less than those for CH_4 fluxes.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

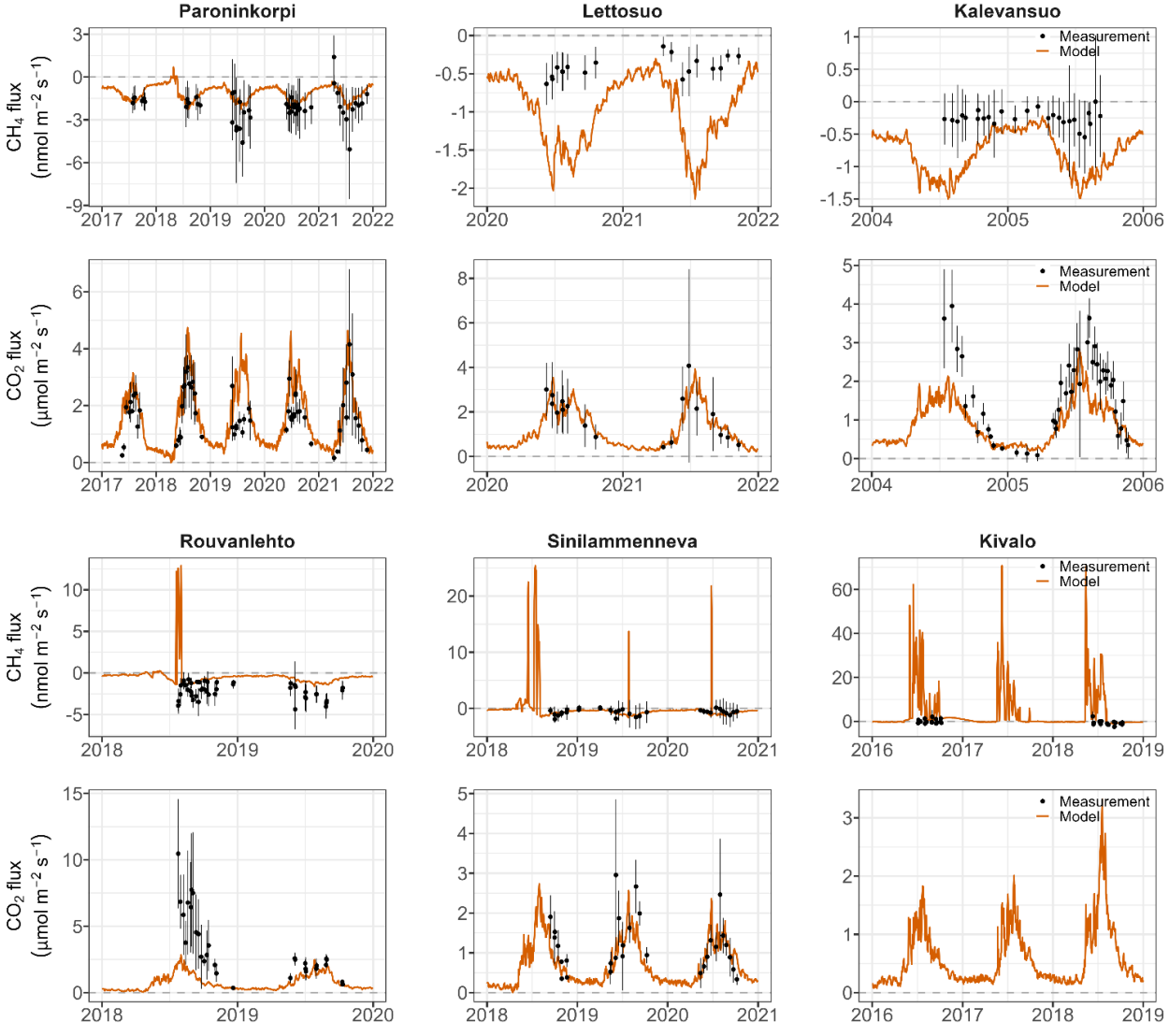


Figure 5. Daily measured (+sd as error bars) and modelled soil CH_4 and CO_2 fluxes (i.e. heterotrophic respiration) in each peatland site simulated with the *baseline* HIMMELI parameters. Above the grey dashed 0-line the flux is positive (towards the atmosphere) and below it, the flux is negative (towards the soil). Note the differences in y axis scales among the sites.

3.3. Sensitivity of simulated fluxes to WTL

The discrepancies between modelled and measured CH_4 fluxes emerged mainly with high WTL (Fig. 6). Yet, the sites in the deep-WTL group (Lettosuo, Paroninkorpi and Kalevansuo) had smaller mean discrepancies between the modelled and measured CH_4 fluxes, compared to the sites in the high-WTL group (Sinilammenneva, Kivalo, Rouvanlehto) (Fig. 6). Generally, high WTL at sites (Kivalo, Rouvanlehto, Sinilammenneva) caused high anaerobic respiration peaks (Fig. 4). Specifically, this happened when modelled WTL rose to -0.2 m (below the soil surface), or higher. Thus, the anaerobic

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

respiration peaks were more prominent when the WTL stayed high over several days. The high peaks emerged when WTL stayed in the upper rapidly decomposing soil layer, acrotelm, which was rather thick at some study sites, ranging from 0.19 to 0.35 m, across the sites (Table B1). The discrepancies between modelled and measured CO_2 fluxes also increased with WTL, but not as systematically as with the CH_4 fluxes (Fig. 6).

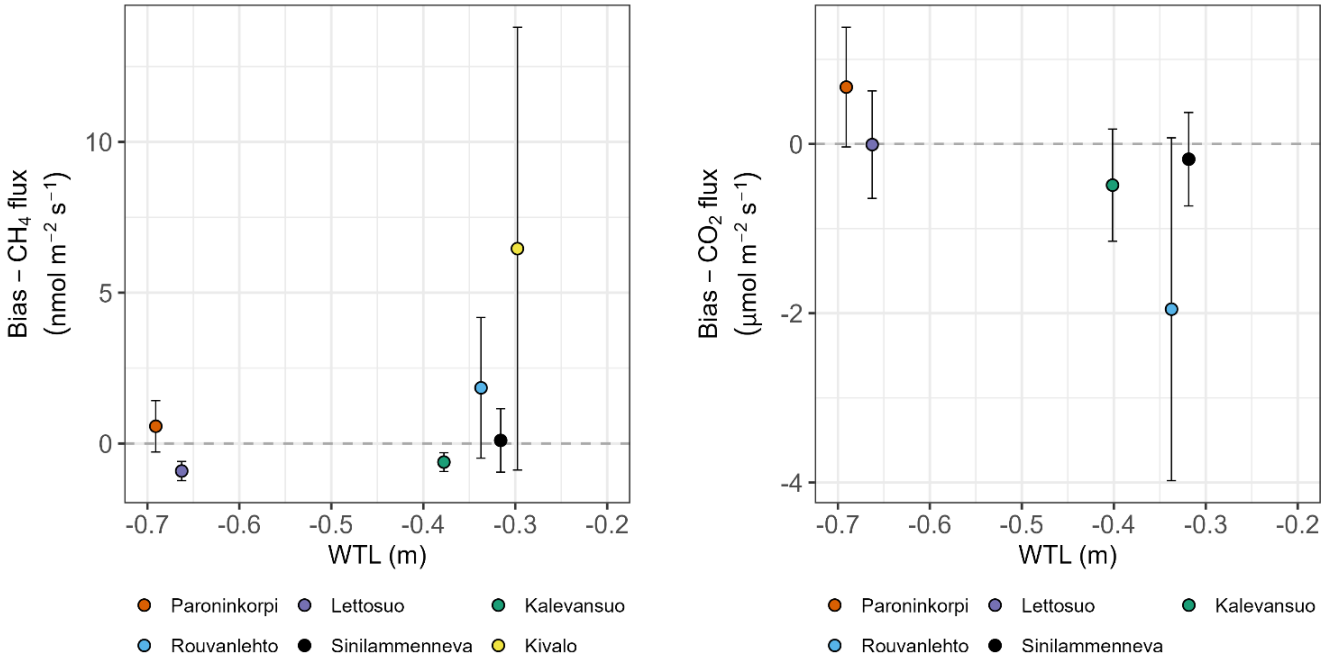


Figure 6. The mean±sd differences (here "bias") calculated as modelled-measured fluxes by using the *baseline* simulations. CH_4 fluxes (on the left) and CO_2 fluxes, i.e. heterotrophic respiration (on the right) vs. mean measured water table levels on each study site. Modelled fluxes used here are the ±5 day moving averages.

3.4 Simulation of CH_4 fluxes with modified HIMMELI parameters

3.4.1 Sensitivity test

We tested sensitivity of modelled CH_4 fluxes to changes in parameters governing CH_4 production and oxidation in HIMMELI by using one high-WTL site (Kivalo) and one deep-WTL site (Paroninkorpi). The change in *fm* (i.e. potential fraction of anaerobic respiration becoming CH_4) had in general a major impact on the modelled CH_4 flux, especially at the high-WTL site (Kivalo) (Fig. 7). It mainly influenced high CH_4 emission peaks. Meanwhile, the change in V_{o10} (i.e. CH_4 oxidation potential at 10 °C) had only a minor effect on both high- and deep-WTL sites (Fig. 7). At the high-WTL site, the modelled mean CH_4 flux ranged between 0.64 and 31.79 nmol m^{-2} s^{-1} among the change in *fm* values, and between 3.25 and 4.47 nmol m^{-2} s^{-1} when the V_{o10} was changed. At the deep-WTL site, the CH_4 flux ranged much less, between -1.10 and -0.54 nmol m^{-2} s^{-1} when *fm* was changed and -1.55 and -0.49 nmol m^{-2} s^{-1} when V_{o10} was changed.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

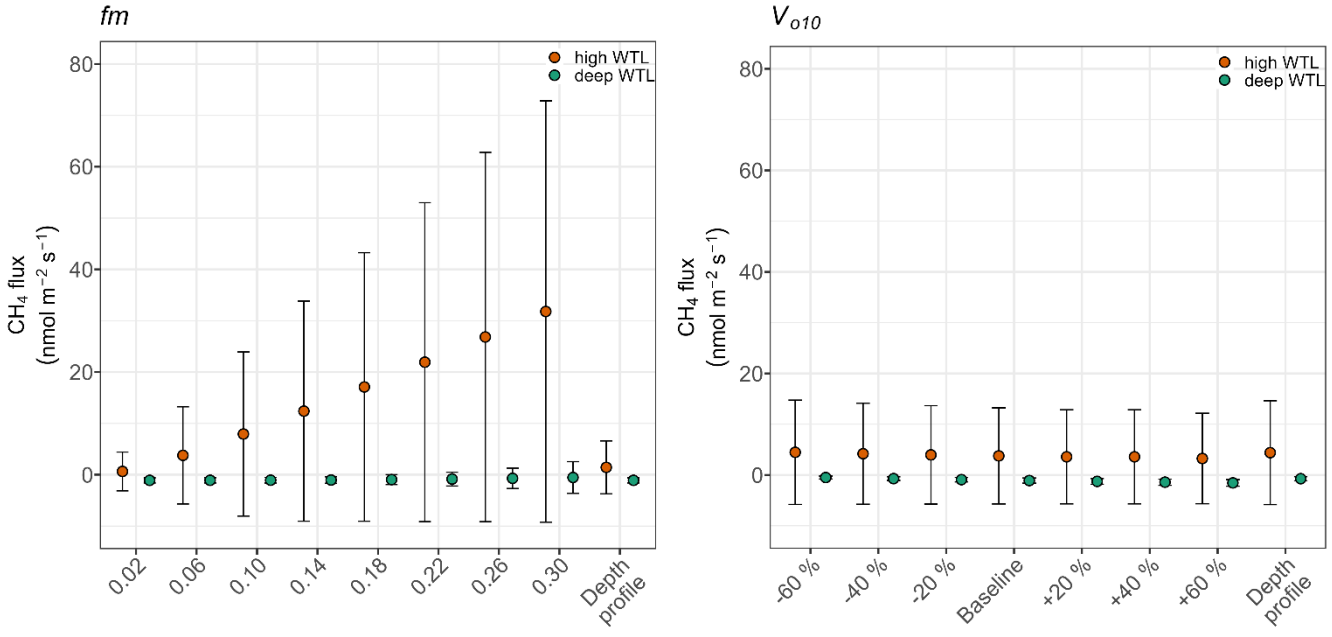


Figure 7. Sensitivity test results for mean (±sd) CH_4 flux with deep-WTL site (Paroninkorpi) and high-WTL site (Kivalo), with changed *fm* (potential fraction of anaerobic respiration becoming CH_4, on the left) and with changed V_{o10} (CH_4 oxidation potential at 10 °C, on the right).

3.4.2 Simulated CH_4 fluxes with the CH_4 parameterization for high- and deep-WTL sites

The alternative HIMMELI CH_4 parameter versions demonstrated that the reduction of *fm* significantly reduced high CH_4 emission peaks at high-WTL sites (Fig. 8). This had a particularly strong impact on the Kivalo site, which had very high simulated emission peaks with the *baseline* HIMMELI version. RMSE values were between 0.53 and 2.59 nmol m^{-2} s^{-1}, which was a clear improvement to the *baseline* (Table 4). The *fm* profile version, i.e. *fm* varying at varying peat depths, also improved the model prediction (Fig. 8). At Rouvanlehto and at Sinilammenneva, the profile version alone was sufficient to eliminate the high emission peaks. However, at Kivalo, due to the very high emission peaks, the profile version was not sufficient to remove the peaks. RMSE values were between 0.52 and 4.39 nmol m^{-2} s^{-1}.

Reduction in V_{o10} improved the model prediction at two deep-WTL sites, Lettosuo and Kalevansuo, while predictions deteriorated at Paroninkorpi site (Fig. 8). The CH_4 flux simulated with profile version (i.e. reducing the CH_4 oxidation potential value only at some peat layers) and the reduction in the whole peat profile did not differ significantly. The RMSE values for the reduction of V_{o10} along the peat profile ranged 0.18–1.63 nmol m^{-2} s^{-1} and the RMSE values of the profile version ranged 0.25–1.36 nmol m^{-2} s^{-1}. The change in V_{o10} affected the range of the modelled CH_4 flux. Smaller V_{o10} caused smaller range, and bigger V_{o10} bigger range.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

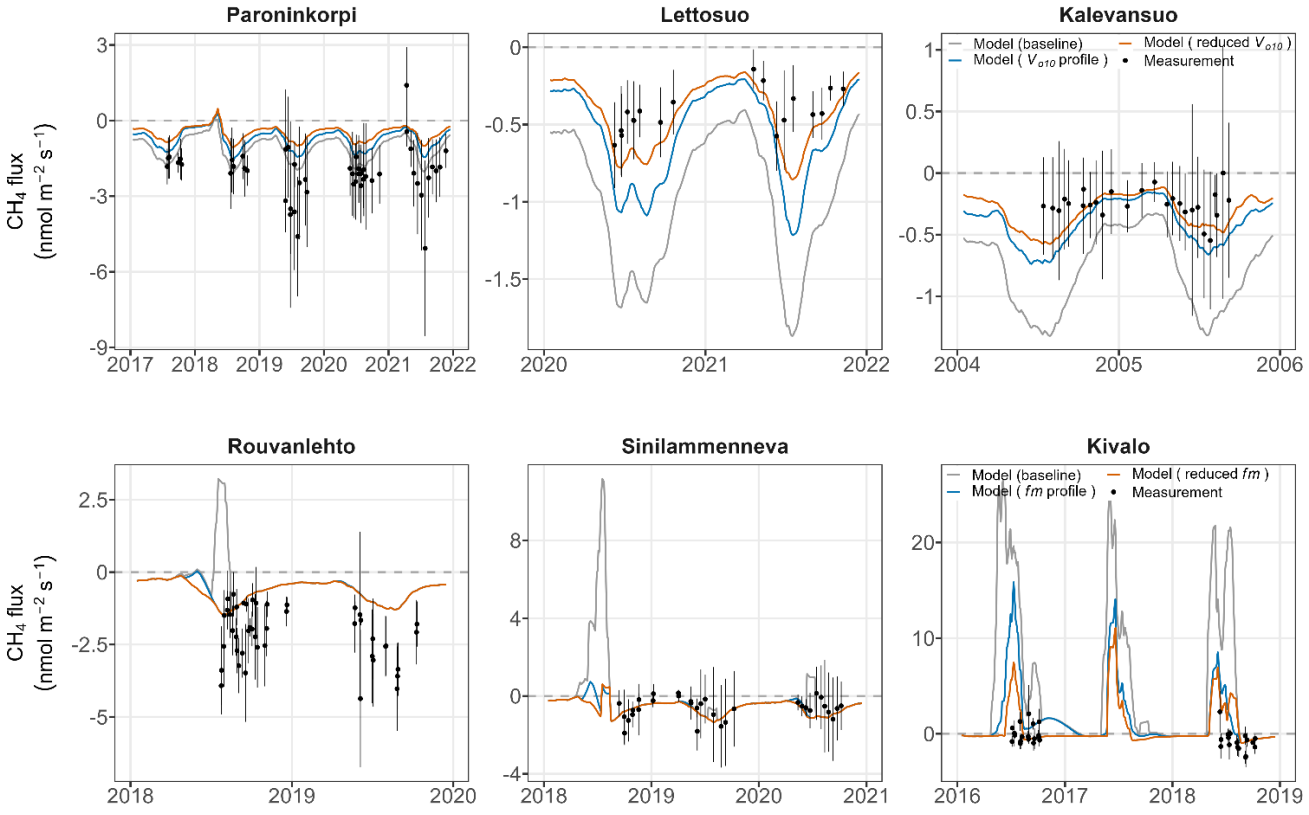


Figure 8. Soil CH_4 fluxes simulated with different HIMMELI parameter versions at deep-WTL sites (top row), and at high-WTL sites (bottom row) compared with measurements. Modelled values are plotted as 30-day moving mean values for each parameter version. Error bars show the standard deviation of the daily measurements.

4 Discussion

4.1 Simulation of environmental drivers

We demonstrated that our model was able to simulate the key environmental drivers (WTL, soil temperature) adequately well at the six drained peatland forest sites. The comparison between ERA5-Land and weather station data revealed some discrepancies in minimum temperatures (Fig. 3). During the growing season differences likely occur primarily during nighttime and therefore have no impact on photosynthesis. The monthly precipitation estimates of ERA5-Land were slightly higher than the corresponding station estimates. Therefore, the drought limitation in photosynthesis in JSBACH may have been lower than with the station data. In addition, precipitation influences the simulated WTL indirectly through its effect on soil moisture, from which WTL is derived. Therefore, some overestimated high WTL values may have been affected by high precipitation estimates in the forcing data. All in all, the differences both in air temperature and precipitation may have a small impact in $YASSO_{peatland}$ soil carbon model, which in turn impacts the input variables used in HIMMELI, i.e. soil temperature

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

and anaerobic respiration. However, this effect is minor and using ERA5-Land and station data would likely result in similar soil carbon uptake and emissions in HIMMELI.

The measured WTL had a considerable between-site variation and therefore, applying *default* parameter values (i.e. common WTL parameter values at all sites) caused significant bias in simulated WTL (Fig. B2). Since WTL is an important factor affecting the transport of gases in HIMMELI, it is important to reach the general level and range of WTL accurately. Therefore, we used the *site-level fitted* WTL for each site in our HIMMELI simulations. This has been also noted in earlier studies with HIMMELI. Li et al. (2024), with the same model set-up, fitted WTL of Lettosuo site depending on the harvesting intensity, since the change in LAI_{max} was not sufficient to adjust the WTL after harvesting. Similarly, e.g. Gao et al. (2025) used the averaged bias between the measured and modelled WTL to correct WTL predicted by JULES model in multiple pristine peatland sites. In our study, the model-measurement agreement in simulating WTL varied between sites from moderate to very strong correlation (Table 3). At Kivalo site, the lack of continuous measurement data caused uncertainty in simulating the WTL. The between-site variation in the correspondences between modelled and measured WTL may be also affected by some site-specific characteristics, which were not considered in the model. For example, Leppä et al. (2020) simulated WTL from multiple drained peatland forests with a process-based model and reported that description of the peat type (Carex /Sphagnum peat) and drainage characteristics (especially ditch spacing) improved the model prediction.

4.2. Simulated soil CH_4 and CO_2 fluxes and their sensitivity to WTL

When *baseline* HIMMELI version was applied, the model predicted occasional CH_4 emissions at three of the study sites. However, despite these peaks, the model on average predicted five of the six sites (except Kivalo) as CH_4 sinks (Table 4). On average, forestry-drained peatland soils are mainly small sinks of CH_4 (i.e. the flux is from the atmosphere into the soil) based on both the measured soil CH_4 fluxes of this study and literature (Lohila et al., 2011; Ojanen et al., 2010). Generally, already a 5 cm drop of WTL below soil surface effectively reduces CH_4 emissions (Zou et al., 2022). Local CH_4 emission hotspots may occur, e.g. from open-water surfaces of drainage ditches (Minkkinen and Laine, 2006; Rissanen et al., 2023) or aerenchymatous plants transporting CH_4 from the peat soil (Ge et al., 2024). However, CH_4 via plant transport is generally of minor importance in drained peatland forests with rather low WTL, since aerenchymatous plants coverage is low. The daily flux measurements used in this study may leave out some of the naturally occurring spatial variability in the soil CH_4 fluxes. For example, the measurements did not include the drainage ditches.

We demonstrated that sites with generally high WTL had larger discrepancies between modelled and measured CH_4 fluxes, compared to sites with deep WTL, due to the high anaerobic respiration peaks. This can be explained by the fact that in the model, WTL raises and stays in acrotelm, i.e. in the rapidly decomposing topsoil. This leads to temporarily increase in anaerobic respiration. For example, Kivalo site exhibited both thickest modelled acrotelm on average and periods of high modelled WTL resulting in temporarily enhanced anaerobic respiration and the greatest overestimation of modelled CH_4 fluxes among all study sites. Similarly, Li et al. (2024) demonstrated with the same model set-up, that high anaerobic respiration was simulated when WTL stayed in the acrotelm, but WTL staying in the catotelm (i.e. the bottom soil layers) did not cause the

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

same effect. In our study, differences in acrotelm thickness among the study sites in principle contribute to the observed between-site differences in simulated CH_4 fluxes. We initiated our site simulations in 1990, and the length of the simulation period before measurement data varied among sites. However, site-specific differences in acrotelm thicknesses are driven mainly by WTL and weather conditions, rather than by the length of the simulation periods, and the overall results would not have likely changed with small changes in the acrotelm thicknesses.

The $YASSO_{peatland}$ model with the strict acrotelm-catotelm division is designed primarily for pristine peatlands and therefore, applying it to simulate the soil carbon pools in forestry-drained peatlands, raises some uncertainties. In pristine peatlands, acrotelm is traditionally defined as the active, seasonally water-saturated upper soil layer that receives recently senesced (i.e. fresh) plant material, while catotelm is the more inert, permanently water-saturated layer (Ingram, 1978). These two layers differ by e.g. hydraulic conductivity and bulk density. However, peatland drainage for forestry alters these conditions by making the acrotelm drier and more compacted, increasing its bulk density, which tends to rise with stand volume, and accelerating the decomposition of organic matter (Minkkinen and Laine, 1998). Another limitation may be that the $YASSO_{peatland}$ model does not allow fresh litter inputs to enter the catotelm. While plant roots may transport fresh carbon to deeper soil layers and thereby enhance the decomposition of old peat (Fontaine et al., 2007), evidence from forestry-drained peatlands suggests that such effect may be weak. For example Linkosalmi et al. (2023) observed, with two same study sites (Lettosuo and Kalevansuo) that the fresh carbon actually reduced the decomposition of old peat.

The model prediction was generally better for the soil–atmosphere CO_2 fluxes (i.e. heterotrophic respiration in this study), than for the CH_4 fluxes, since there was less variation in the model bias between the sites (Table 4). Some exceptions occurred at some sites and at some years, when the model underestimated CO_2 fluxes during the growing season. For the Kalevansuo site, the simulated soil temperature was slightly underestimated, which may explain the underestimation in the heterotrophic respiration. Soil temperature is important control of heterotrophic respiration in drained peatland forests (Mäkiranta et al., 2009). Other important controlling factors include WTL and soil nutrient status (Ojanen et al., 2010). HIMMELI model version, which was used as the *baseline* in our study, was calibrated for Lettosuo, which is a nutrient-rich site (Li et al., 2024). Given that our study included only two nutrient-poor sites (Kalevansuo and Sinilammenneva), it is difficult to determine whether soil nutrient status influenced the bias in simulated heterotrophic respiration. We recommend investigating the effect of soil nutrient status on model bias with forestry-drained peatlands as a future model development. Additionally, the effect of recent forest management, e.g., timber harvesting, was not considered in our study. Harvesting elevates the WTL, because there remains less trees transpiring, thus affecting both heterotrophic respiration- and CH_4 fluxes in soil (Korkiakoski et al., 2019; Korrensalo et al., 2026). Thus, further research is needed to improve our understanding of the combined effects of forest management and diverse site characteristics in forestry-drained peatlands.

4.3. Sensitivity of the modelled CH_4 fluxes to the CH_4 parameterization

Despite using a very small value for *fm* (i.e. potential fraction of anaerobic respiration becoming CH_4) in *baseline* runs, it was not sufficient to prevent high CH_4 emission peaks from appearing, in cases when WTL rose to -0.2 m (below the soil surface),

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

or higher. The sensitivity test revealed a major difference in the response of CH_4 fluxes simulated by HIMMELI to CH_4 parameterization between the high-WTL and deep-WTL sites (Fig. 7). Similarly, Shahriyer et al. (2026) found with the LandscapeDNDC model that the modelled soil–atmosphere CH_4 flux at a drained peatland forest was sensitive to the changes in WTL. In our study, at the high-WTL sites, where prominent CH_4 emission peaks occurred, the reduction in *fm* (i.e. potential fraction of anaerobic respiration becoming CH_4) successfully reduced high peaks. Ueyama et al. (2023) reported the CH_4 production being more important process to explain between-site differences in CH_4 emissions than CH_4 oxidation or transport, particularly at high-WTL sites characterized by a thin oxic layer. In our study, the varying CH_4 production along the peat depth reduced successfully high CH_4 emission peaks at some study sites (Fig. 8). This could be considered as a potential model development in future studies, as CH_4 production potential is significantly affected by WTL and is typically highest at the WTL and in the peat layer immediately below it in forestry-drained peatlands (Galand et al., 2005).

We found that the change in V_{o10} parameter value (i.e. CH_4 oxidation potential at 10 °C) affected the general level of simulated soil CH_4 flux in the deep-WTL sites (Fig. 8). In fact, this adjustment modestly improved the model prediction at two of the deep-WTL sites, Kalevansuo and Lettosuo, compared to the *baseline* HIMMELI version. However, model performance deteriorated at one site, Paroninkorpi, which had clearly higher soil CH_4 uptake than the other two sites. It is challenging to accurately model this between-site and interannual variation in CH_4 uptake, which may arise from several factors related to e.g. meteorological conditions, drainage activities and site characteristics. However, the magnitude of the bias in simulated CH_4 fluxes at deep-WTL sites was sufficiently small to be considered acceptable.

5 Conclusions

We applied a process-based JSBACH-HIMMELI model to simulate the key environmental drivers and soil–atmosphere CH_4 and CO_2 fluxes from multiple forestry-drained peatlands. The model showed generally good agreement between observed and simulated environmental drivers (soil temperature and WTL). We identified WTL as the key source of uncertainty in simulating the soil–atmosphere fluxes, especially for CH_4 fluxes. The key factors contributing to this uncertainty were the large difference in decomposition rates between the bottom soil layers (catotelm) and topsoil layers (acrotelm) and the relatively thick modelled acrotelms, both of which promoted high anaerobic respiration. In addition, the sensitivity test and alternative HIMMELI CH_4 parameter versions revealed CH_4 parameterization being a minor source of uncertainty in the modelled CH_4 fluxes, but having a potential to improve the model prediction, especially at the high-WTL sites. These findings highlight the importance of accurately simulating water table levels in drained peatlands and of developing soil carbon models that explicitly represent the specific properties and processes of drained peatland soils.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Appendix A: Meteorological data

Table A1. List of the weather stations where air temperature and precipitation data was extracted. Data is openly available in https://www.ilmatieteenlaitos.fi/havaintojen-lataus.

Site	Data period	Weather station
Rouvanlehto	2018–2019	Varkaus Kosulanniemi
Kivalo	2016–2018	Rovaniemi, Apukka
Kalevansuo	2004–2005	Hyvinkää, Hyvinkäänkylä
Lettosuo	2020–2021	Somero, Salkola
Paroninkorpi	2017–2021	Temperature: Hämeenlinna Katinen, except 7.6.2019–28.2.2020 from Hattula-Lepaa. Precipitation: Hämeenlinna Katinen, except 13.7.2018–29.2.2020 from Hattula-Lepaa.
Sinilammenneva	2018–2020	Juupajoki, Hyytiälä

Appendix B: JSBACH simulations - supporting material

Table B1. Carbon pool thicknesses at each peatland site during the site-specific simulation-measurement comparison periods.

Site	Acrotelm height (m)	Catotelm height (m)
Rouvanlehto	0.24–0.25	1.06
Kivalo	0.34–0.35	0.55–0.56
Kalevansuo	0.24–0.26	1.98
Lettosuo	0.19–0.20	1.77
Paroninkorpi	0.22–0.24	1.27
Sinilammenneva	0.25–0.27	1.02

Table B2. Scaling WTL parameters used in JSBACH simulations.

Site	Parameter m	Parameter n
“default”	2.01	0.36
Rouvanlehto	1.24	0.3
Kivalo	0.93	0.13
Kalevansuo	1.78	0.47
Lettosuo	3	1.2
Paroninkorpi	3.26	1.21
Sinilammenneva	1.48	0.53

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

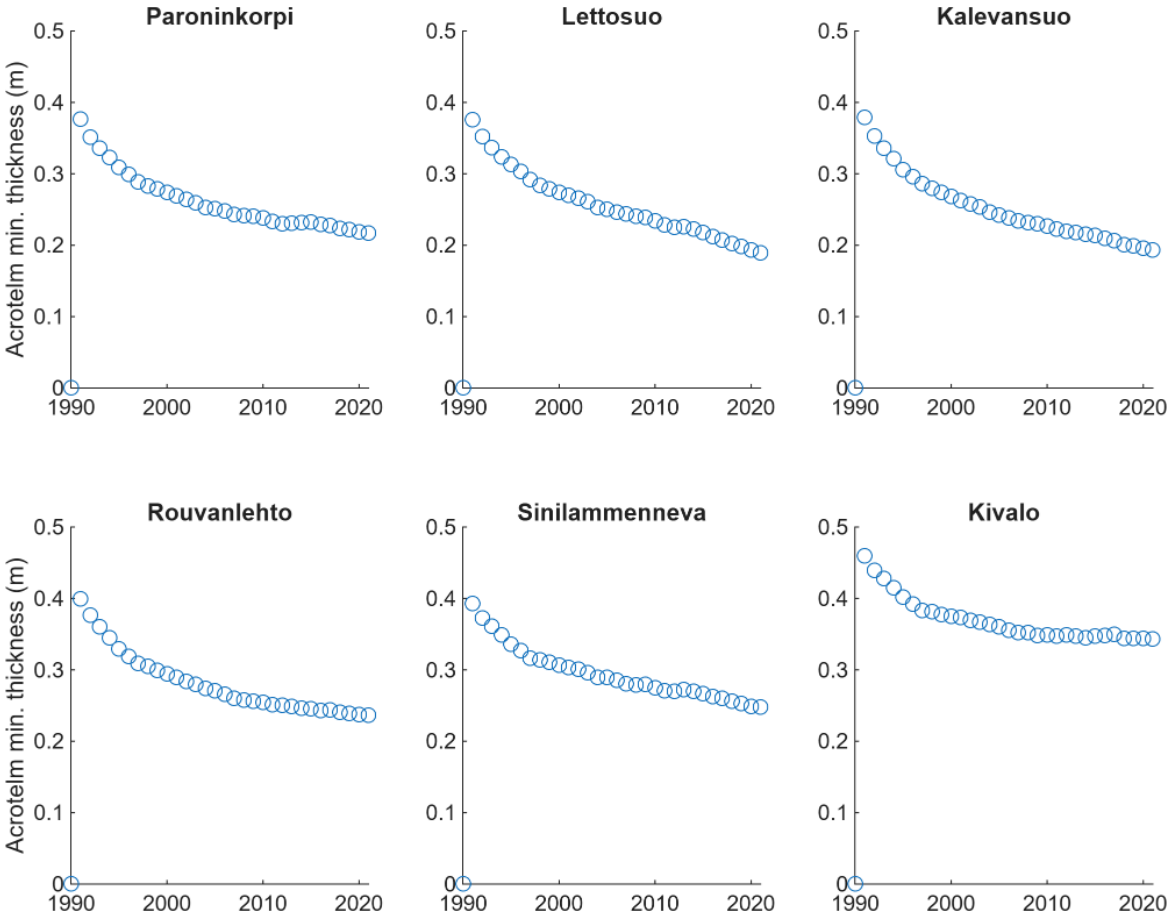


Figure B1. Annual simulated minimum acrotelm thicknesses at each site.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

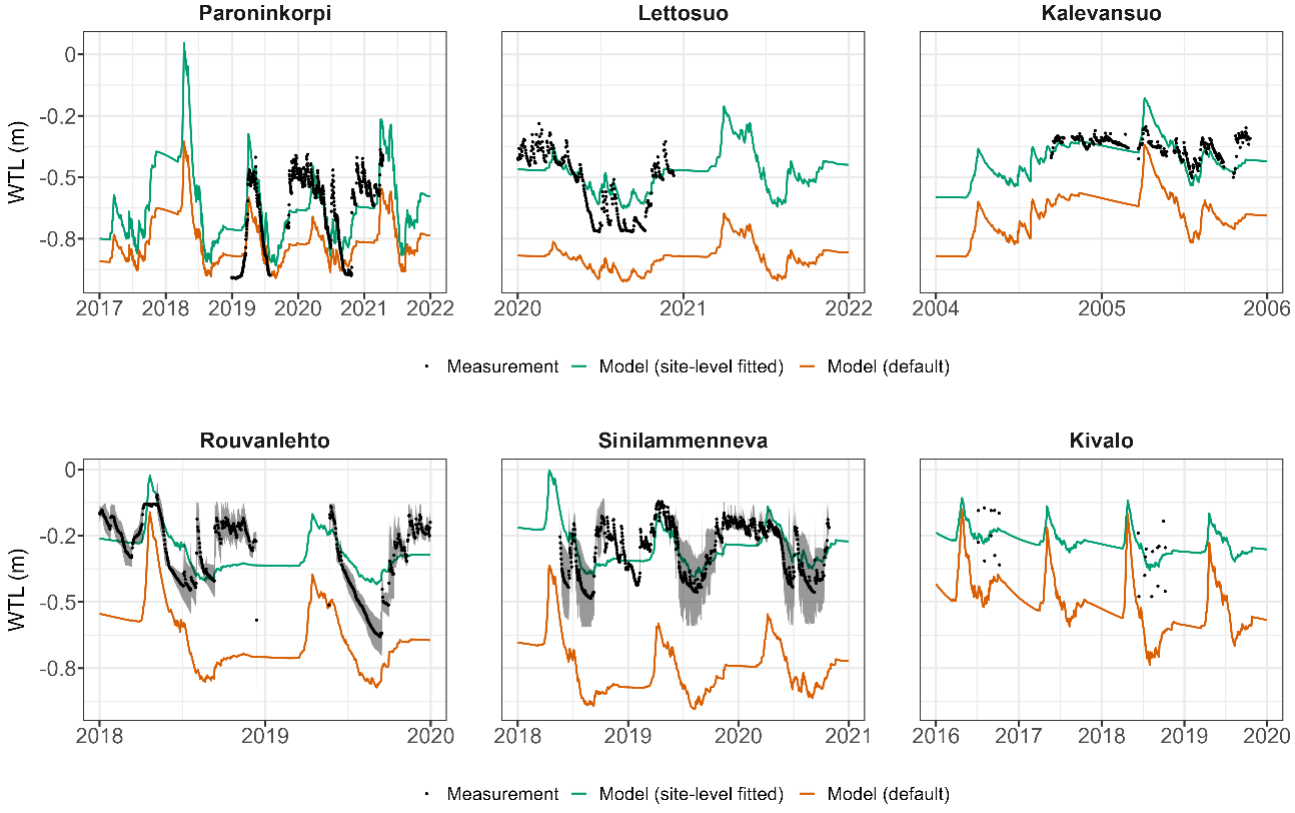


Figure B2. Simulated and measured WTL at each peatland site with two WTL parameter options.

Code and data availability

The JSBACH code is freely available to the scientific community upon request to the Max Planck Institute for Meteorology. The HIMMELI model code will be made publicly available upon publication.

The measurement and model data in this study will be made publicly available in Zenodo upon publication (doi: 10.5281/zenodo.23686731) and can be provided to the referees upon request.

Author contributions

MR, XL, EE designed the study. TM, TA, AL, XL and MR contributed to setting up the model. AL implemented modifications to the HIMMELI model code. JA, JJ, RL, ALo, KM, RM, PO, AP and MP provided the measurement data to validate the model. KM, MR, RM and EE secured the funding of the work. EE carried out the simulations and prepared the manuscript with contributions from all co-authors.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We acknowledge the use of Copilot-AI tool for language refinement and assistance with code improvement during the manuscript preparation. All scientific interpretations, analyses, and conclusions were developed and verified by the authors.

Financial support

This study has received financial support from Maj and Tor Nessling foundation (grant number 3676) and from the Research Council of Finland, project RESPEAT (grant numbers 341749 and 341753) and MeWeN (grant number 371040), the UNITE Flagship funded by the Research Council of Finland (grant number 374286). We also want to acknowledge the funding from the Research Council of Finland to Centre of Excellence in Peatlands, Climate Change and Ecological Restoration (grant number 374132).

References

Appiah Mensah, A., Petersson, H., Saarela, S., Goude, M., and Holmström, E.: Using heterogeneity indices to adjust basal area – Leaf area index relationship in managed coniferous stands, Forest Ecology and Management, 458, 117699, https://doi.org/10.1016/j.foreco.2019.117699, 2020.

Blodau, C.: Carbon cycling in peatlands — A review of processes and controls, Environ. Rev., 10, 111–134, https://doi.org/10.1139/a02-004, 2002.

Evans, C. D., Peacock, M., Baird, A. J., Artz, R. R. E., Burden, A., Callaghan, N., Chapman, P. J., Cooper, H. M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R. P., Helfter, C., Heppell, C. M., Holden, J., Jones, D. L., Kaduk, J., Levy, P., Matthews, R., McNamara, N. P., Misselbrook, T., Oakley, S., Page, S. E., Rayment, M., Ridley, L. M., Stanley, K. M., Williamson, J. L., Worrall, F., and Morrison, R.: Overriding water table control on managed peatland greenhouse gas emissions, Nature, 593, 548–552, https://doi.org/10.1038/s41586-021-03523-1, 2021.

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., and Rumpel, C.: Stability of organic carbon in deep soil layers controlled by fresh carbon supply, Nature, 450, 277–280, https://doi.org/10.1038/nature06275, 2007.

Galand, P. E., Juottonen, H., Fritze, H., and Yrjälä, K.: Methanogen Communities in a Drained Bog: Effect of Ash Fertilization, Microb Ecol, 49, 209–217, https://doi.org/10.1007/s00248-003-0229-2, 2005.

Gao, Y., Burke, E. J., Chadburn, S. E., Raivonen, M., Markkanen, T., Aurela, M., Flanagan, L. B., Fortuniak, K., Humphreys, E., Lohila, A., Li, T., Mammarella, I., Nevalainen, O., Nilsson, M. B., Pawlak, W., Tsuruta, A., Yang, H., and Aalto, T.: Assessing modelled methane emissions over northern wetlands by the JULES-HIMMELI model, Science of The Total Environment, 980, 179526, https://doi.org/10.1016/j.scitotenv.2025.179526, 2025.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Ge, M., Korrensalo, A., Laiho, R., Kohl, L., Lohila, A., Pihlatie, M., Li, X., Laine, A. M., Anttila, J., Putkinen, A., Wang, W., and Koskinen, M.: Plant-mediated CH4 exchange in wetlands: A review of mechanisms and measurement methods with implications for modelling, Science of The Total Environment, 914, 169662, https://doi.org/10.1016/j.scitotenv.2023.169662, 2024.

Goll, D. S., Brovkin, V., Liski, J., Raddatz, T., Thum, T., and Todd-Brown, K. E. O.: Strong dependence of CO2 emissions from anthropogenic land cover change on initial land cover and soil carbon parametrization, Global Biogeochemical Cycles, 29, 1511–1523, https://doi.org/10.1002/2014GB004988, 2015.

Hagemann, S. and Stacke, T.: Impact of the soil hydrology scheme on simulated soil moisture memory, Clim Dyn, 44, 1731–1750, https://doi.org/10.1007/s00382-014-2221-6, 2015.

Ingram, H. a. P.: Soil Layers in Mires: Function and Terminology, Journal of Soil Science, 29, 224–227, https://doi.org/10.1111/j.1365-2389.1978.tb02053.x, 1978.

Intergovernmental Panel On Climate Change (Ipcc): Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press, https://doi.org/10.1017/9781009157896, 2023.

Jaatinen, K., Tuittila, E.-S., Laine, J., Yrjälä, K., and Fritze, H.: Methane-Oxidizing Bacteria in a Finnish Raised Mire Complex: Effects of Site Fertility and Drainage, Microb Ecol, 50, 429–439, https://doi.org/10.1007/s00248-005-9219-x, 2005.

Jauhiainen, J., Heikkinen, J., Clarke, N., He, H., Dalsgaard, L., Minkkinen, K., Ojanen, P., Vesterdal, L., Alm, J., Butlers, A., Callesen, I., Jordan, S., Lohila, A., Mander, Ü., Óskarsson, H., Sigurdsson, B. D., Søgaard, G., Soosaar, K., Kasimir, Å., Bjarnadottir, B., Lazdins, A., and Laiho, R.: Reviews and syntheses: Greenhouse gas emissions from drained organic forest soils – synthesizing data for site-specific emission factors for boreal and cool temperate regions, Biogeosciences, 20, 4819–4839, https://doi.org/10.5194/bg-20-4819-2023, 2023.

Juottonen, H., Hynninen, A., Nieminen, M., Tuomivirta, T. T., Tuittila, E.-S., Nousiainen, H., Kell, D. K., Yrjälä, K., Tervahauta, A., and Fritze, H.: Methane-Cycling Microbial Communities and Methane Emission in Natural and Restored Peatlands, Applied and Environmental Microbiology, 78, 6386–6389, https://doi.org/10.1128/AEM.00261-12, 2012.

Kallingal, J. T., Scholze, M., Miller, P. A., Lindström, J., Rinne, J., Aurela, M., Vestin, P., and Weslien, P.: Assimilating multi-site eddy-covariance data to calibrate the wetland CH_4 emission module in a terrestrial ecosystem model, Biogeosciences, 22, 4061–4086, https://doi.org/10.5194/bg-22-4061-2025, 2025.

Kettunen, A., Kaitala, V., Lehtinen, A., Lohila, A., Alm, J., Silvola, J., and Martikainen, P. J.: Methane production and oxidation potentials in relation to water table fluctuations in two boreal mires, Soil Biology and Biochemistry, 31, 1741–1749, https://doi.org/10.1016/S0038-0717(99)00093-0, 1999.

Kleinen, T., Mikolajewicz, U., and Brovkin, V.: Terrestrial methane emissions from the Last Glacial Maximum to the preindustrial period, Climate of the Past, 16, 575–595, https://doi.org/10.5194/cp-16-575-2020, 2020.

Korkiakoski, M., Tuovinen, J.-P., Penttilä, T., Sarkkola, S., Ojanen, P., Minkkinen, K., Rainne, J., Laurila, T., and Lohila, A.: Greenhouse gas and energy fluxes in a boreal peatland forest after clear-cutting, Biogeosciences, 16, 3703–3723, https://doi.org/10.5194/bg-16-3703-2019, 2019.

Korkiakoski, M., Ojanen, P., Tuovinen, J.-P., Minkkinen, K., Nevalainen, O., Penttilä, T., Aurela, M., Laurila, T., and Lohila, A.: Partial cutting of a boreal nutrient-rich peatland forest causes radically less short-term on-site CO2 emissions than clear-cutting, Agricultural and Forest Meteorology, 332, 109361, https://doi.org/10.1016/j.agrformet.2023.109361, 2023.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Korrensalo, A., Mäkiranta, P., Laiho, R., Anttila, J., Launiainen, S., Minkkinen, K., Mehtätalo, L., Mäkipää, R., Penttilä, T., Saarinen, M., Sarkkola, S., and Ojanen, P.: Effect of tree harvesting on heterotrophic soil respiration in boreal drained peatland forests, Forest Ecology and Management, 612, 123730, https://doi.org/10.1016/j.foreco.2026.123730, 2026.

Laine, J., Vasander, H., Hotanen, J.-P., Nousiainen, H., Saarinen, M., and Penttilä, T.: Suotyypit ja turvekankaat - opas kasvupaikkojen tunnistamiseen, Metsäkustannus, Hämeenlinna, 2012.

Laurila, T., Aurela, M., Hatakka, J., Hotanen, J.-P., Jauhiainen, J., Korkiakoski, M., Korpela, L., Koskinen, M., Laiho, R., Lehtonen, A., Leppä, K., Linkosalmi, M., Lohila, A., Minkkinen, K., Mäkelä, T., Mäkiranta, P., Nieminen, M., Ojanen, P., Peltoniemi, M., Penttilä, T., Rainne, J., Rautakoski, H., Saarinen, M., Salovaara, P., Sarkkola, S., and Mäkipää, R.: Set-up and instrumentation of the greenhouse gas measurements on experimental sites of continuous cover forestry, Natural Resources Institute Finland (Luke), 2021.

Leppä, K., Hökkä, H., Laiho, R., Launiainen, S., Lehtonen, A., Mäkipää, R., Peltoniemi, M., Saarinen, M., Sarkkola, S., and Nieminen, M.: Selection Cuttings as a Tool to Control Water Table Level in Boreal Drained Peatland Forests, Front. Earth Sci., 8, https://doi.org/10.3389/feart.2020.576510, 2020.

Li, X., Markkanen, T., Korkiakoski, M., Lohila, A., Leppänen, A., Aalto, T., Peltoniemi, M., Mäkipää, R., Kleinen, T., and Raivonen, M.: Modelling alternative harvest effects on soil CO2 and CH4 fluxes from peatland forests, Science of The Total Environment, 951, 175257, https://doi.org/10.1016/j.scitotenv.2024.175257, 2024.

Linkosalmi, M., Lohila, A., and Biasi, C.: Stronger negative priming effect and lower basal respiration rates in nutrient-poor as compared to nutrient-rich forestry-drained peatland, Rapid Communications in Mass Spectrometry, 37, e9540, https://doi.org/10.1002/rcm.9540, 2023.

Liu, L., Ciais, P., Nguyen, T. H., Xi, Y., Qiu, C., Salmon, E., Kalhori, A., Guimbaud, C., Peichl, M., Ratcliffe, J. L., Noumonvi, K. D., and Li, X.: Modeling the impact of drainage on peatland CO_2 and CH_4 fluxes and its underlying drivers, Biogeosciences, 23, 2277–2308, https://doi.org/10.5194/bg-23-2277-2026, 2026.

Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J.-P., Penttilä, T., Ojanen, P., and Laurila, T.: Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink, Biogeosciences, 8, 3203–3218, https://doi.org/10.5194/bg-8-3203-2011, 2011.

Majasalmi, T., Eisner, S., Astrup, R., Fridman, J., and Bright, R. M.: An enhanced forest classification scheme for modeling vegetation–climate interactions based on national forest inventory data, Biogeosciences, 15, 399–412, https://doi.org/10.5194/bg-15-399-2018, 2018.

Mäkiranta, P., Laiho, R., Fritze, H., Hytönen, J., Laine, J., and Minkkinen, K.: Indirect regulation of heterotrophic peat soil respiration by water level via microbial community structure and temperature sensitivity, Soil Biology and Biochemistry, 41, 695–703, https://doi.org/10.1016/j.soilbio.2009.01.004, 2009.

Minkkinen, K. and Laine, J.: Effect of forest drainage on the peat bulk density of pine mires in Finland, Can. J. For. Res., 28, 178–186, https://doi.org/10.1139/x97-206, 1998.

Minkkinen, K. and Laine, J.: Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry, Plant Soil, 285, 289–304, https://doi.org/10.1007/s11104-006-9016-4, 2006.

Minkkinen, K., Ojanen, P., Penttilä, T., Aurela, M., Laurila, T., Tuovinen, J.-P., and Lohila, A.: Persistent carbon sink at a boreal drained bog forest, Biogeosciences, 15, 3603–3624, https://doi.org/10.5194/bg-15-3603-2018, 2018.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Mozafari, B., Bruen, M., Donohue, S., Renou-Wilson, F., and O'Loughlin, F.: Peatland dynamics: A review of process-based models and approaches, Science of The Total Environment, 877, 162890, https://doi.org/10.1016/j.scitotenv.2023.162890, 2023.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, Earth System Science Data, 13, 4349–4383, https://doi.org/10.5194/essd-13-4349-2021, 2021.

Nilsson, M. and öQuist, M.: Partitioning Litter Mass Loss into Carbon Dioxide and Methane in Peatland Ecosystems, in: Carbon Cycling in Northern Peatlands, American Geophysical Union (AGU), 131–144, https://doi.org/10.1029/2008GM000819, 2009.

Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Soil–atmosphere CO2, CH4 and N2O fluxes in boreal forestry-drained peatlands, Forest Ecology and Management, 260, 411–421, https://doi.org/10.1016/j.foreco.2010.04.036, 2010.

Ojanen, P., Minkkinen, K., and Penttilä, T.: The current greenhouse gas impact of forestry-drained boreal peatlands, Forest Ecology and Management, 289, 201–208, https://doi.org/10.1016/j.foreco.2012.10.008, 2013.

Peltoniemi, M., Li, Q., Turunen, P., Tupek, B., Mäkiranta, P., Leppä, K., Müller, M., Rissanen, A. J., Laiho, R., Anttila, J., Jauhiainen, J., Koskinen, M., Lehtonen, A., Ojanen, P., Pihlatie, M., Sarkkola, S., Vainio, E., and Mäkipää, R.: Soil GHG dynamics after water level rise – Impacts of selection harvesting in peatland forests, Science of The Total Environment, 901, 165421, https://doi.org/10.1016/j.scitotenv.2023.165421, 2023.

Petrescu, A. M. R., Qiu, C., McGrath, M. J., Peylin, P., Peters, G. P., Ciais, P., Thompson, R. L., Tsuruta, A., Brunner, D., Kuhnert, M., Matthews, B., Palmer, P. I., Tarasova, O., Regnier, P., Lauerwald, R., Bastviken, D., Höglund-Isaksson, L., Winiwarter, W., Etiope, G., Aalto, T., Balsamo, G., Bastrikov, V., Berchet, A., Brockmann, P., Ciotoli, G., Conchedda, G., Crippa, M., Dentener, F., Groot Zwaaftink, C. D., Guizzardi, D., Günther, D., Haussaire, J.-M., Houweling, S., Janssens-Maenhout, G., Kouyate, M., Leip, A., Leppänen, A., Lugato, E., Maisonnier, M., Manning, A. J., Markkanen, T., McNorton, J., Muntean, M., Oreggioni, G. D., Patra, P. K., Perugini, L., Pison, I., Raivonen, M. T., Saunois, M., Segers, A. J., Smith, P., Solazzo, E., Tian, H., Tubiello, F. N., Vesala, T., van der Werf, G. R., Wilson, C., and Zaehle, S.: The consolidated European synthesis of CH_4 and N_2O emissions for the European Union and United Kingdom: 1990–2019, Earth System Science Data, 15, 1197–1268, https://doi.org/10.5194/essd-15-1197-2023, 2023.

Programme, U. N. E.: Global Peatlands Assessment: The State of the World's Peatlands - Evidence for Action toward the Conservation, Restoration, and Sustainable Management of Peatlands, https://doi.org/10.59117/20.500.11822/41222, 2022.

Qiu, C., Zhu, D., Ciais, P., Guenet, B., Krinner, G., Peng, S., Aurela, M., Bernhofer, C., Brümmer, C., Bret-Harte, S., Chu, H., Chen, J., Desai, A. R., Dušek, J., Euskirchen, E. S., Fortuniak, K., Flanagan, L. B., Friborg, T., Grygoruk, M., Gogo, S., Grünwald, T., Hansen, B. U., Holl, D., Humphreys, E., Hurkuck, M., Kiely, G., Klatt, J., Kutzbach, L., Largeron, C., Laggoun-Défarge, F., Lund, M., Lafleur, P. M., Li, X., Mammarella, I., Merbold, L., Nilsson, M. B., Olejnik, J., Ottosson-Löfvenius, M., Oechel, W., Parmentier, F.-J. W., Peichl, M., Pirk, N., Peltola, O., Pawlak, W., Rasse, D., Rinne, J., Shaver, G., Schmid, H. P., Sottocornola, M., Steinbrecher, R., Sachs, T., Urbaniak, M., Zona, D., and Ziemblinska, K.: ORCHIDEE-PEAT (revision 4596), a model for northern peatland CO_2, water, and energy fluxes on daily to annual scales, Geoscientific Model Development, 11, 497–519, https://doi.org/10.5194/gmd-11-497-2018, 2018.

Raivonen, M., Smolander, S., Backman, L., Susiluoto, J., Aalto, T., Markkanen, T., Mäkelä, J., Rinne, J., Peltola, O., Aurela, M., Lohila, A., Tomasic, M., Li, X., Larmola, T., Juutinen, S., Tuittila, E.-S., Heimann, M., Sevanto, S., Kleinen, T., Brovkin, V., and Vesala, T.: HIMMELI v1.0: HelsinkI Model of MEthane buiLd-up and emIssion for peatlands, Geoscientific Model Development, 10, 4665–4691, https://doi.org/10.5194/gmd-10-4665-2017, 2017.

https://doi.org/10.5194/egusphere-2026-6692
Preprint. Discussion started: 12 November 2026
© Author(s) 2026. CC BY 4.0 License.

Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, https://doi.org/10.1002/jame.20022, 2013.

Reick, C. H., Gayler, V., Goll, D., Hagemann, S., Heidkamp, M., Nabel, J. E. M. S., Raddatz, T., Roeckner, E., Schnur, R., and Wilkenskjeld, S.: JSBACH 3 - The land component of the MPI Earth System Model: documentation of version 3.2, https://doi.org/10.17617/2.3279802, 2021.

Rissanen, A. J., Ojanen, P., Stenberg, L., Larmola, T., Anttila, J., Tuominen, S., Minkkinen, K., Koskinen, M., and Mäkipää, R.: Vegetation impacts ditch methane emissions from boreal forestry-drained peatlands—Moss-free ditches have an order-of-magnitude higher emissions than moss-covered ditches, Front. Environ. Sci., 11, https://doi.org/10.3389/fenvs.2023.1121969, 2023.

Roulet, N. T., Ash, R., Quinton, W., and Moore, T.: Methane flux from drained northern peatlands: Effect of a persistent water table lowering on flux, https://doi.org/10.1029/93GB01931, 1993.

Sarkkola, S., Hökkä, H., Koivusalo, H., Nieminen, M., Ahti, E., Päivänen, J., and Laine, J.: Role of tree stand evapotranspiration in maintaining satisfactory drainage conditions in drained peatlands, Can. J. For. Res., 40, 1485–1496, https://doi.org/10.1139/X10-084, 2010.

Shahriyer, A. H., Kraus, D., Markkanen, T., Korkiakoski, M., Rautakoski, H., Orttenvuori, S., Gao, Y., Kajasilta, H., Grote, R., Lohila, A., and Aalto, T.: Evaluation of the LandscapeDNDC model for drained peatland forest managements, LDNDC v1.35.2 (revision 11434), Geoscientific Model Development, 19, 8815–8838, https://doi.org/10.5194/gmd-19-8815-2026, 2026.

Thum, T., Nabel, J. E. M. S., Tsuruta, A., Aalto, T., Dlugokencky, E. J., Liski, J., Luijkx, I. T., Markkanen, T., Pongratz, J., Yoshida, Y., and Zaehle, S.: Evaluating two soil carbon models within the global land surface model JSBACH using surface and spaceborne observations of atmospheric CO_2, Biogeosciences, 17, 5721–5743, https://doi.org/10.5194/bg-17-5721-2020, 2020.

Tuomi, M., Thum, T., Järvinen, H., Fronzek, S., Berg, B., Harmon, M., Trofymow, J. A., Sevanto, S., and Liski, J.: Leaf litter decomposition—Estimates of global variability based on Yasso07 model, Ecological Modelling, 220, 3362–3371, https://doi.org/10.1016/j.ecolmodel.2009.05.016, 2009.

Ueyama, M., Knox, S. H., Delwiche, K. B., Bansal, S., Riley, W. J., Baldocchi, D., Hirano, T., McNicol, G., Schafer, K., Windham-Myers, L., Poulter, B., Jackson, R. B., Chang, K.-Y., Chen, J., Chu, H., Desai, A. R., Gogo, S., Iwata, H., Kang, M., Mammarella, I., Peichl, M., Sonnentag, O., Tuittila, E.-S., Ryu, Y., Euskirchen, E. S., Göckede, M., Jacotot, A., Nilsson, M. B., and Sachs, T.: Modeled production, oxidation, and transport processes of wetland methane emissions in temperate, boreal, and Arctic regions, Global Change Biology, 29, 2313–2334, https://doi.org/10.1111/gcb.16594, 2023.

Urbanová, Z. and Bárta, J.: Recovery of methanogenic community and its activity in long-term drained peatlands after rewetting, Ecological Engineering, 150, 105852, https://doi.org/10.1016/j.ecoleng.2020.105852, 2020.

Yrjälä, K., Tuomivirta, T., Juottonen, H., Putkinen, A., Lappi, K., Tuittila, E.-S., Penttilä, T., Minkkinen, K., Laine, J., Peltoniemi, K., and Fritze, H.: CH4 production and oxidation processes in a boreal fen ecosystem after long-term water table drawdown, Global Change Biology, 17, 1311–1320, https://doi.org/10.1111/j.1365-2486.2010.02290.x, 2011.

Zou, J., Ziegler, A. D., Chen, D., McNicol, G., Ciais, P., Jiang, X., Zheng, C., Wu, J., Wu, J., Lin, Z., He, X., Brown, L. E., Holden, J., Zhang, Z., Ramchunder, S. J., Chen, A., and Zeng, Z.: Rewetting global wetlands effectively reduces major greenhouse gas emissions, Nat. Geosci., 15, 627–632, https://doi.org/10.1038/s41561-022-00989-0, 2022.