



Representing peatland drainage-ditch hydrology impacts on CO₂ and CH₄ emissions in the ORCHIDEE-PEAT land surface model (r9703)

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Abstract. Peatland drainage through ditching is the common practice for cultivating peatlands. Ditches reduce the water table in surrounding peat soils, reducing methane (CH₄) emissions from the peat surface and increasing soil carbon CO₂ emissions. But the ditch itself receives dissolved carbon and litter inputs and emits these two gases, an overlooked process in greenhouse gases (GHG) assessments. We present here a parameterization of drainage ditch hydrology and GHG emission processes within the ORCHIDEE-PEAT global land surface model to simulate CO₂ and CH₄ emissions from peatland drainage ditches. The model prescribes subgrid ditch area and depth in the fraction of each model grid cell covered by peat, and simulates lateral carbon transfers from soils to dissolved organic carbon (DOC), soil organic carbon (SOC) pools in the bottom of ditches, diffusion of dissolved gases, ditch water discharge, and kinetic gas exchange of GHG at the ditch air-water surface. Simulated gas exchange velocities and CH₄ emissions are within the range of field measurements and meta-analysis data. Our simulation results show that ditch emissions offset 7-13% of drainage-induced peat soils CH₄ emission reductions. Simulated ditch CO₂ fluxes were small or negative, partly reflecting current model limitations in which lateral dissolved CO₂ transport from peat soil to ditch is not represented. This identifies dissolved CO₂ transport as an important process for further model development. This model development is transferable to other models and can contribute to more accurate assessments of peatland ditch drainage hydrology and GHG fluxes by enabling the simultaneous consideration of upland and aquatic ditch fluxes.

1 Introduction

Undisturbed peatlands with their waterlogged conditions generally act as sinks of CO₂ and sources of methane (CH₄) (Frolking et al., 2011). Peatland drainage for conversion to forestry, farming, peat extraction, leads to an increase in CO₂ emission and a decrease in CH₄ emission (Freeman et al., 1992; Nykänen et al., 1995). However, drainage ditches used to drain peat can remain a significant source of CH₄ emission (Minkinen and Laine, 2006; Niu et al., 2024; Peacock et al., 2017; Roulet and Moore, 1995; Schrier-Uijl et al., 2011). Methane gets transported into ditches by lateral drainage from the surrounding peat. It



is also produced in-situ from anoxic decomposition of carbon dissolved in the ditch and in sediments at the ditch bottom. According to the global meta-analysis of Peacock et al. (2021), ditch emissions can offset the CH₄ reduction effect of drainage by 18%, and mean ditch CH₄ emissions of $64.6 \pm 11.1 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ are comparable to those from streams, reservoirs and tropical wetlands. A recent meta-analysis, which incorporated a more comprehensive dataset of annual CH₄ emissions and paired measurements from near-pristine and drained peatlands, reported a similar ditch emission rate of $69.5 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ and a ditch-induced offset of 12% (Gan et al., 2024). Both studies highlighted the necessity of including ditch emissions in assessments of the drainage impact on the greenhouse gas balance of peatlands. In addition to direct CO₂ emissions to the atmosphere, drainage ditches may enhance lateral dissolved organic carbon (DOC) export from peatlands, representing an additional pathway of carbon loss. However, CO₂ emissions from peatland ditches have received much less attention in both experimental and modelling studies.

Previously, we conducted simulations using the ORCHIDEE-PEAT model to estimate the trade-offs between CO₂ and CH₄ emissions resulting from drainage scenarios across 10 peatland sites in temperate and boreal peatlands (Liu et al., 2026a). However, only emissions through the peat surface were accounted for in that study, while emissions from ditches were omitted. The objective of this study is to simulate CO₂ and CH₄ fluxes from drainage ditches in temperate and boreal peatlands by introducing a physical parameterization of ditch hydrology and carbon processes into ORCHIDEE-PEAT. The model represents lateral drainage and CH₄ transport from adjacent peat, as well as CH₄ production and oxidation in both the ditch and ditch-bottom soil. CH₄ is transported from the ditch-bottom soil to the ditch water through diffusion and ebullition, while exchange between the ditch water and the atmosphere occurs through diffusive gas exchange. Direct ebullitive CH₄ emissions from the ditch-bottom peat soil to the atmosphere and plant-mediated transport are not explicitly represented.

2 Method

2.1 General ditch description

In the peatland soil tile of the model grid cell (Qiu et al., 2018; 2019), we assumed that drainage ditches are arranged parallel to each other, with a ditch spacing of s . Each ditch has a u-shaped profile of width, w and of depth, h . The ditch is filled by a one layered water column and underneath is a discretized ditch soil column. The ditch soil column remains permanently saturated because it is continuously covered by ditch water. **Figure 1** illustrates the hydrological configuration of the ditch–peatland unit (**Fig. 1a**) and associated carbon and gases transformations (**Fig. 1b**).

In the model, the soil profile is vertically discretized to represent depth-dependent hydrological and biogeochemical processes. A targeted water table depth is prescribed to the model at each time step to simulate drainage. Above this level, water from the soil is drained laterally into the ditch, while below, the peat soil is saturated. The detailed processes of vertical peat soil infiltration and water table depth forcing are described in our previous study (Liu et al., 2026a). Briefly, vertical soil water flow in the ORCHIDEE-PEAT model is simulated with a diffusion model using peat specific vertical profiles of hydraulic conductivity and soil water saturation (Ducharne et al., 2018). Here, we added a component representing lateral drainage from



the adjacent peat soil to the ditch (**Fig. 1a**). The ditch water depth, D [m], varies in response to the lateral drainage from the adjacent peat, rainfall falling directly onto the ditch, and ditch discharge to streams, (F_{out}), as described in **Section 2.2**.

Biogeochemical processes in the ditch soil are simulated similarly to those in the peat soil, including redox-dependent decomposition, CH_4 oxidation, CH_4 and O_2 diffusion, and CH_4 ebullition but excluding plant-mediated CH_4 transport (Qiu et al., 2018; Salmon et al., 2022). Redox-dependent decomposition comprises aerobic decomposition where O_2 is available and anaerobic decomposition under oxygen-limited conditions, whereas CH_4 oxidation occurs in presence of dissolved O_2 (dO_2) in the ditch (**Fig. 1b**).

The ditch water column is treated as a single, well mixed reactive compartment, such that dissolved constituents are assumed to be spatially homogeneous within the water column. Dissolved organic carbon (DOC), dissolved inorganic carbon (dCO_2), dissolved methane (dCH_4), and dO_2 are stored, transported, and transformed within this compartment. DOC enters the ditch water column through litter inputs and DOC leaching from SOC of the adjacent peat soil, as described in **Section 2.3**, and DOC in the ditch supports aerobic and anaerobic decomposition. Dissolved CH_4 supplied from the adjacent peat soil and from the underlying ditch soil column can be oxidized in the ditch water column where dCH_4 and dO_2 coexist. In contrast, dCO_2 produced in the terrestrial peat is not transported laterally to the ditch; dCO_2 in ditch water is generated only by processes represented within the ditch system. CH_4 produced in the underlying ditch soil can enter the ditch water through diffusion and ebullition, while CO_2 produced by ditch-soil carbon decomposition and CH_4 oxidation contributes to the ditch-water dCO_2 pool. O_2 can enter the ditch water from the atmosphere through air–water gas exchange.

The gas-exchange between the ditch water surface and the atmosphere differs from that in terrestrial peat soils. In terrestrial peat soil, CO_2 generated in the soil escapes directly to the atmosphere, while O_2 and CH_4 diffuse between the soil and the atmosphere. In the ditch, the saturated soil column capped by water cannot exchange gases with the atmosphere directly, and only the overlying water column does. Gases produced in the ditch soil enter the water column before they can be emitted to the atmosphere. Ditch emissions are controlled by gas production and oxidation fluxes in both compartments, which are used to simulate dissolved-gas concentrations in the water column, and emissions are simulated from gas exchange across the air–water interface.

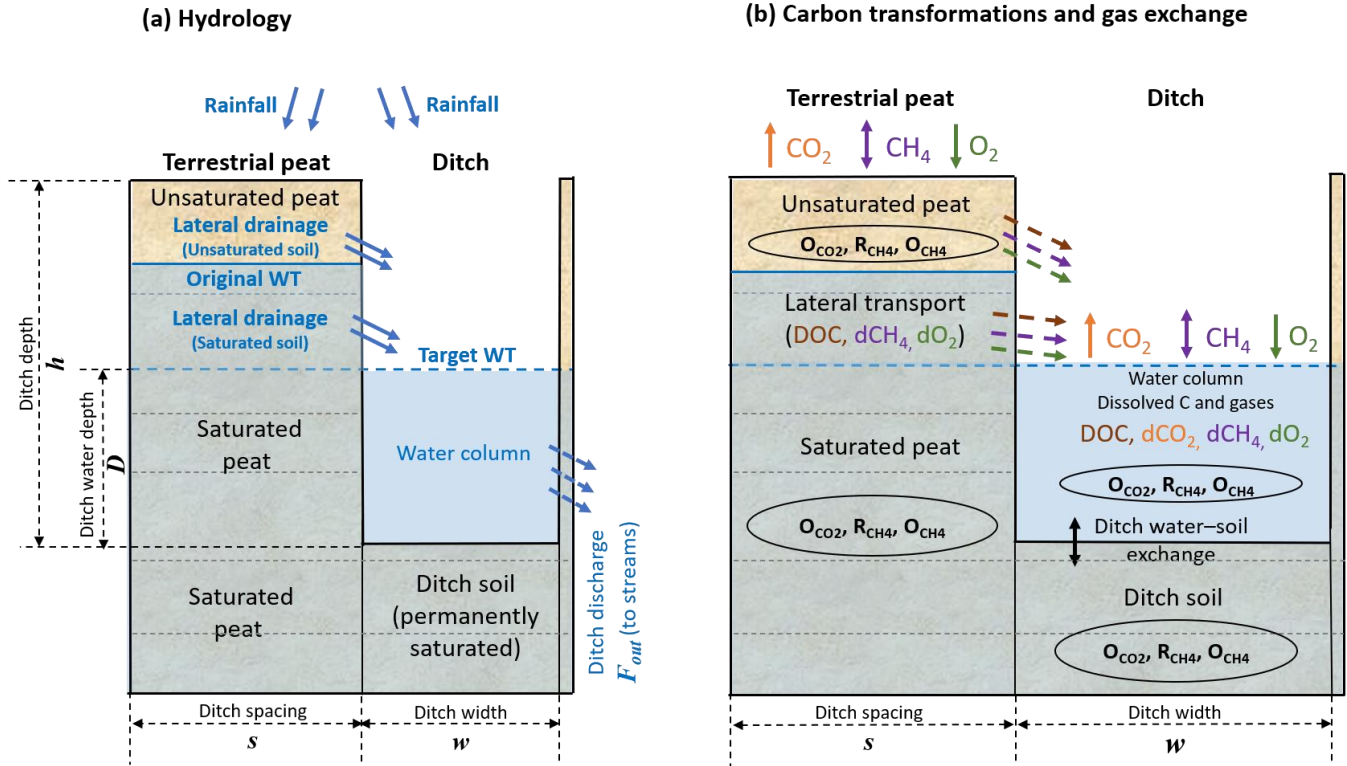


Figure 1. Conceptual representation of hydrological and biogeochemical processes in a ditch-peatland unit. The schematic shows one representative cross-section of a repeating ditch-peatland system. (a) Hydrological configuration of the ditch-peatland unit. Rainfall enters both the terrestrial peat and the ditch. Water is transferred laterally from the adjacent terrestrial peat to the ditch through drainage from the unsaturated soil and from the saturated soil between the original water table (Original WT; blue solid line) and the prescribed target water table (Target WT; blue dashed line). The Target WT represents the prescribed peat water table under drainage, while ditch-water depth varies dynamically according to the ditch water balance. The ditch soil below the water column remains permanently saturated. Ditch water is discharged laterally to streams. Ditch depth, ditch water depth, ditch width, and ditch spacing are denoted by h , D , w , and s , respectively. (b) Carbon transformations, dissolved carbon transport, and gas exchange in the same ditch-peatland unit. CO_2 is transported upward toward the atmosphere, whereas O_2 diffuses downward from the atmosphere into the peat and ditch water. CH_4 transport is shown as bidirectional to represent diffusion along concentration gradients and exchange across soil-air and water-air interfaces. Dissolved carbon and gases, including dissolved organic carbon (DOC), $d\text{CH}_4$ and $d\text{O}_2$ are laterally transported from terrestrial peat to the ditch water column. Within the ditch, dissolved carbon and gases are stored and transformed in the water column and exchanged with the underlying ditch soil. Three redox transformations are represented: oxidation of organic carbon to CO_2 (O_{CO_2}), reduction of organic carbon to CH_4 (R_{CH_4}), and oxidation of CH_4 to CO_2 (O_{CH_4}). These processes are represented in terrestrial peat, ditch water, and ditch soil. Orange, purple, green, and blue arrows represent CO_2 , CH_4 , and O_2 , and water transport, respectively. Horizontal gray dashed lines indicate the model vertical discretization of the soil profiles.

2.2 Ditch water balance

The ditch water balance over one time step Δt [s] is illustrated in **Fig. 2**. The ditch water column is treated as a water reservoir receiving water from three sources: lateral drainage from the saturated and unsaturated parts of the adjacent peat (F_{ds} and F_{du}), and direct rainfall onto the ditch surface (F_{pre}). Water is removed from the ditch through discharge to streams (F_{out}). The water balance is expressed as:



$$V^t - V^{t-1} = F_{ds} + F_{du} + F_{pre} - F_{out}, \quad (1)$$

where V^{t-1} and V^t [m^3] denote the ditch water volumes at the beginning and at the end of a model time step, respectively. F_{ds} , F_{du} , and F_{pre} [m^3], denote lateral drainage from saturated peat, lateral drainage from the unsaturated peat, and direct rainfall onto the ditch, respectively, while F_{out} [m^3] denotes ditch discharge to streams during the same time step. The individual terms of the ditch water balance are described below.

Lateral drainage from saturated peat (F_{ds} , green box in Fig. 2). The original water table represents the undisturbed water-table elevation in the adjacent peat before drainage. In the conceptual ditch–peat system, this elevation is used to define a reference ditch-water storage, V_{ref} [m^3]. Specifically, V_{ref} is the ditch-water volume that would correspond geometrically to a ditch water level at the elevation of the original water table (labelled “Original WT” in Fig. 2). It is therefore a reference maximum storage rather than the actual ditch-water volume at a given time step or the physical maximum storage capacity of the ditch. When the actual ditch-water volume V^{t-1} is below V_{ref} , as it is usually the case except after e.g. a very heavy rainfall event, water from the saturated peat between the original and target water tables drains laterally into the ditch. As V^{t-1} approaches V_{ref} , the difference $V_{ref} - V^{t-1}$ decreases and therefore reduces the magnitude of F_{ds} . In this way, V_{ref} represents the tendency of the saturated-peat drainage to replenish the ditch-water storage after that the water has been removed by the ditch discharge, rather than to be a prescribed ditch-water level that must be reached. Because the ditch discharge occurs within the same model time step as lateral drainage from the peat, the simulated ditch-water storage can remain below V_{ref} . The saturated-peat drainage is represented using a characteristic timescale τ_{in} [s]:

$$F_{ds} = \frac{(V_{ref} - V^{t-1})}{\tau_{in}} \times \Delta t. \quad (2)$$

Lateral drainage from unsaturated peat (F_{du} , pink box in Fig. 2). Water from the unsaturated part of the adjacent peat soil above the prescribed target water table is drained laterally into the ditch. The drainage volume obtained after one model time step is calculated as:

$$F_{du} = K_{eff} \times A_{du} \times \Delta t, \quad (3)$$

where K_{eff} [m s^{-1}] is the effective lateral drainage velocity, incorporating the effect of horizontal hydraulic conductivity and the lateral hydraulic gradient, and A_{du} [m^2] is the lateral cross-sectional area of the drained peat layers facing the ditch. This area is calculated as $A_{du} = H_{du} \times l$, where l [m] is the total ditch length represented at the sub-grid cell level and H_{du} [m] is the thickness of the unsaturated peat layers that contribute to the lateral drainage to the ditch.

Direct rainfall input (F_{pre} , yellow box in Fig. 2). The water volume supplied by precipitation directly onto the ditch surface during one model time step is calculated as:

$$F_{pre} = P \times A_{ditch} \times \Delta t, \quad (4)$$

where P [m s^{-1}] is the precipitation rate and A_{ditch} [m^2] is the total open-water surface area of the ditch within the model grid
 140 cell, calculated as $A_{\text{ditch}} = w \times l$, where w [m] is the ditch width and l [m] is the total ditch length in the model grid cell.

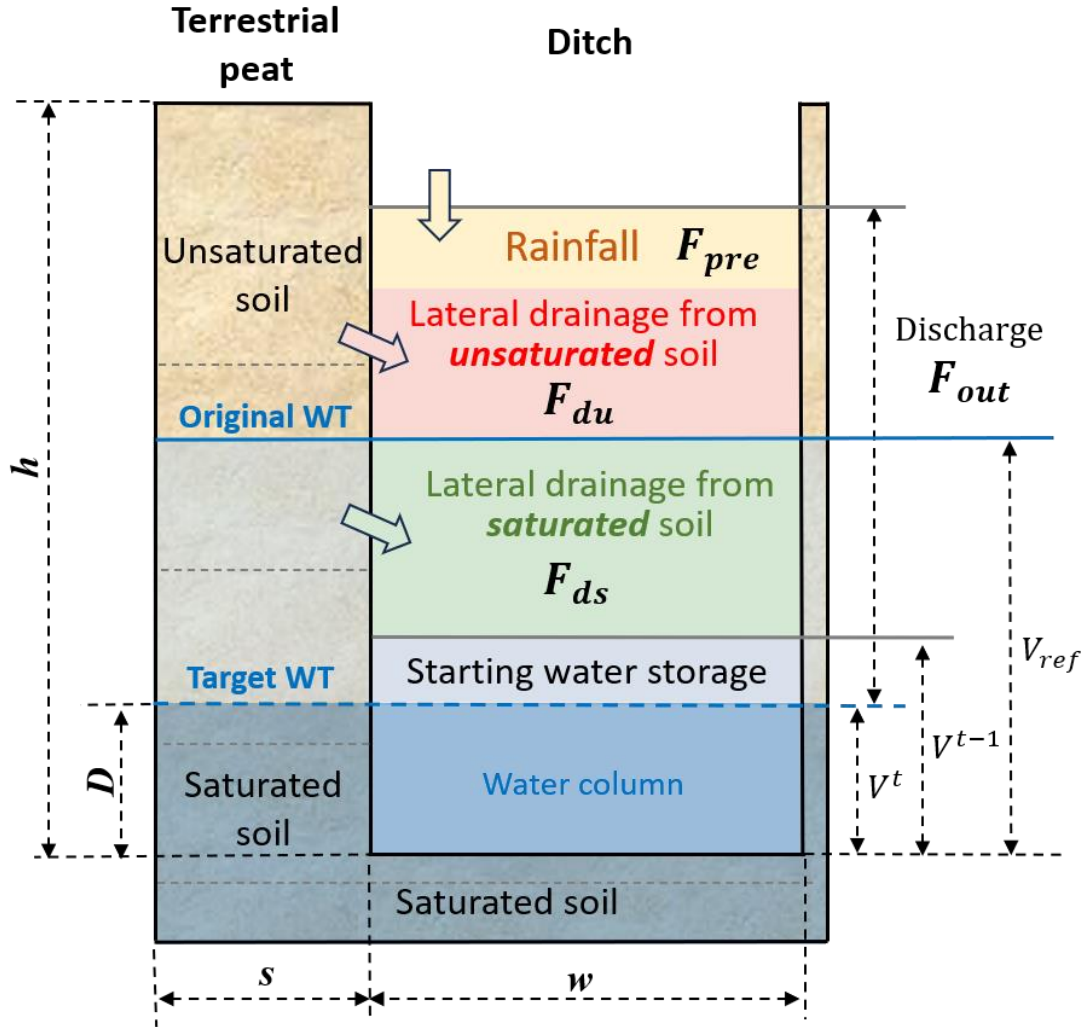


Figure 2. Schematic representation of the ditch water balance over one model time step Δt . The ditch water storage changes from V^{t-1} [m^3] at the beginning of the time step to V^t [m^3] at the end of the time step in response to the direct rainfall to the ditch, F_{pre} [m^3], the drainage from the unsaturated peat, F_{du} [m^3], the drainage from saturated peat, F_{ds} [m^3], and the ditch discharge to streams, F_{out} [m^3]. The original water-table elevation defines a reference ditch-water storage, V_{ref} [m^3], corresponding geometrically to the ditch-water volume at that elevation. V_{ref} provides the reference state toward which drainage from the saturated peat tends to replenish the ditch storage, rather than a maximum ditch-storage capacity. The starting ditch-water storage V^{t-1} is illustrated schematically by its corresponding water level. The ditch depth, the ditch water depth, the ditch width, and the ditch spacing are denoted by h [m], D [m], w [m], and s [m], respectively.

2.3 Carbon distribution

150 Carbon is represented by multiple pools distributed among four physical domains shown in **Fig. 3**: the litter, the terrestrial peat soil, the ditch water, and the ditch soil. The litter is represented by the metabolic and the structural pools, as in the original



ORCHIDEE-PEAT model (Qiu et al., 2018; 2019). The terrestrial peat soil contains the active, the slow, and the passive soil organic carbon (SOC) pools, as originally included in the ORCHIDEE-PEAT soil carbon module and based on the CENTURY model (Parton et al., 1988). The ditch water column contains two dissolved organic carbon (DOC) pools, the labile DOC and the refractory DOC, whereas the ditch soil contains three SOC pools—the active, the slow, and the passive pools—corresponding to those represented in the terrestrial peat soil.

Litter inputs are produced by vegetation and are calculated separately for each peat plant functional type (PFT). The metabolic and the structural litter are further separated into above- and below-ground components. For peat PFTs, a fraction of the carbon released from decomposed above-ground litter can be transferred to the ditch-water DOC pools, whereas below-ground litter remains within the terrestrial peat-soil carbon pools. These litter and associated carbon transfers are first calculated separately for each peat PFT and then combined to a PFT-weighted mean before being used by the ditch module. This weighted-mean applies only to peatland carbon inputs, because peatland and non-peatland carbon pools are treated independently. For simplicity, the ditch-water DOC and the ditch-soil SOC pools themselves have no PFT subclass. The SOC pools in both the terrestrial peat soil and the ditch soil are vertically discretized following the model soil layers, although this vertical structure is not represented in **Fig. 3**. The vertical redistribution of SOC among soil layers follows the existing ORCHIDEE-PEAT formulation (Qiu et al., 2019).

Carbon movements among the pools are presented by the arrows in **Fig. 3**. Two pathways supply the carbon to the ditch-water DOC pools. First, a fraction of the carbon released from decomposed above-ground litter is transferred to the ditch water, with metabolic litter contributing to the labile DOC pool and structural litter to the refractory DOC pool. This allocation is controlled by a coefficient $f_{lit,ditch}$, which represents the fraction of peatland surface occupied by ditches and therefore acts as a spatial partitioning factor rather than a biogeochemical conversion coefficient. It is approximated by the ratio of ditch width (w) to ditch spacing (s), and is set to 0.05 (5×10^{-2}) in the default configuration. Second, the active and the slow SOC pools in the terrestrial peat soil are assumed to be leached by the drainage water to the labile and the refractory DOC pools entering the ditch water, respectively. This pathway is controlled by a conversion factor $f_{SOC \rightarrow DOC}$, prescribed as 0.1% in the default configuration. At the ditch water / underlying soil at the ditch bed interface, DOC is transferred back from the ditch water into the SOC pools in the upper few centimetres (set to 0.1 m) of the ditch soil, mimicking the deposition of organic-rich ‘sediment’ material at the ditch bed. This redistribution scheme is adapted from the ORCHIDEE MICT-LEAK model framework (Bowring et al., 2019). Carbon transfers among the active, the slow, and the passive SOC pools in the ditch soil is implemented similarly to that in the terrestrial peat soil.

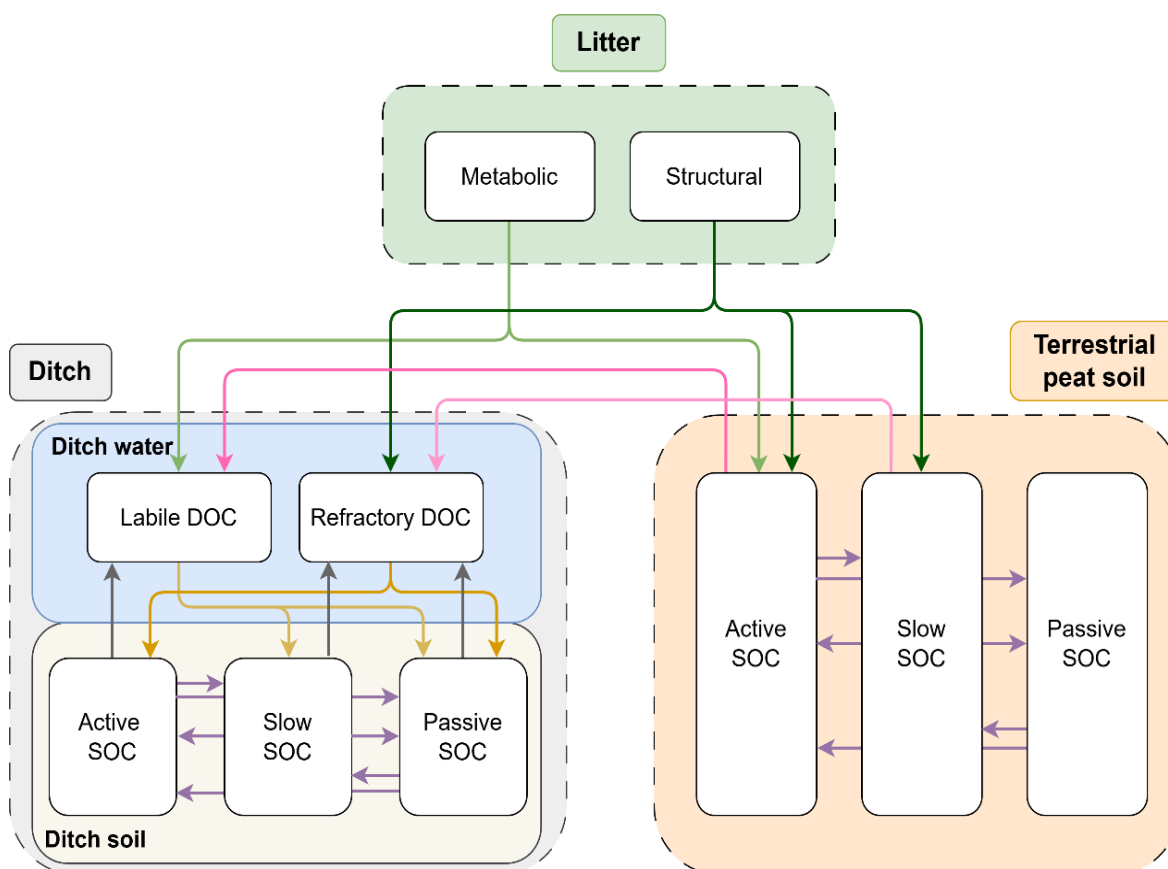


Figure 3. Carbon pools and transfer pathways among litter, terrestrial peat soil, ditch water, and ditch soil. Litter is represented by the metabolic and the structural pools; the terrestrial peat soil and the ditch soil each contain the active, the slow, and the passive soil organic carbon (SOC) pools, whereas the ditch water contains the labile and the refractory dissolved organic carbon (DOC) pools. Arrows represent carbon transfers among the pools. The partial allocation of the litter carbon to the ditch-water DOC and the transfer of carbon from the terrestrial peat-soil SOC to the ditch-water DOC are new additions in the ditch module. Carbon exchange between the ditch-water DOC and the ditch-soil SOC in the upper ditch-soil layers is adapted from the ORCHIDEE MICT-LEAK framework (Bowring et al., 2019). Transfers among the active, the slow, and the passive SOC pools in the ditch soil follow the same scheme as in the terrestrial peat soil.

2.4 DOC and gases in the ditch water

The ditch water is treated as a well-mixed reservoir in which DOC and dissolved-gas concentrations are assumed to be homogeneous. Oxic and anoxic DOC decomposition in the ditch water depends on mean dO_2 concentration and follows the same redox-dependent decomposition framework used for the peat SOC in ORCHIDEE-PEAT (Qiu et al., 2018; Salmon et al., 2022; **Supplementary text Eqs. S1-S4**). Following Bowring et al. (2019), the labile DOC has a turnover time of 0.02 years, approximately 42 times shorter than that of the active SOC pool in the CENTURY model. In the present model, this ratio is applied to the peat soil active SOC residence time from which DOC is sourced, after accounting for the temperature dependence of SOC decomposition, to determine the labile DOC residence time in the ditch water. The refractory DOC residence time is then set to 47 times that of the labile DOC, preserving the refractory-to-labile DOC residence-time ratio used



by Bowring et al. (2019). The carbon exchange between the ditch-water DOC and the ditch-soil SOC is restricted to the top layer of the ditch soil, defined as the uppermost 0.1 m (**Fig. 3**). During the decomposition of DOC in the ditch water, 50% of the decomposed DOC is released as CO₂, while the remaining 50% is transferred to the SOC pools of the upper exchange layer. Conversely, when the SOC in the upper ditch soil layer is decomposed, 50% of the decomposed carbon is transferred to the ditch-water DOC and 50% is released as CO₂. Below the upper exchange layer, the ditch-soil SOC does not exchange carbon with the ditch-water DOC, and its decomposition and redistribution among the active, the slow, and the passive SOC pools follow the same scheme as in the terrestrial peat soil.

Methane in the ditch water originates from lateral transport from the drainage water of the adjacent peat, from methanogenesis in the ditch water, and from CH₄ transferred from the underlying ditch soil through diffusion and ebullition. Methane oxidation occurs in the well-mixed ditch water and depends on the availability of dCH_4 and dO_2 . These processes result from the drainage input (R_{drain}), CH₄ production in the ditch water (R_{MG}), CH₄ inputs from the ditch soil from the ebullition (R_{ebul}) and the diffusion (R_{diff}) transport scheme, and CH₄ consumption by oxidation (R_{MOX}). The change in dCH_4 concentration in the ditch water for one model time step is calculated as:

$$[CH_4]^t = [CH_4]^{t-1} + (R_{drain} + R_{MG} + R_{ebul} + R_{diff} - R_{MOX}) \times \Delta t, \quad (5)$$

where $[CH_4]^{t-1}$ and $[CH_4]^t$ [g CH₄ m⁻³ water] are the dCH_4 concentrations in the ditch water at the beginning and at the end of the model time step, respectively. The R terms [g CH₄ m⁻³ water s⁻¹] denote CH₄ fluxes into or out of the ditch-water dCH_4 pool, expressed relative to the ditch-water volume. R_{drain} represents CH₄ inputs associated with lateral drainage from the adjacent peat, R_{MG} represents CH₄ production by methanogenesis in the ditch water, R_{ebul} and R_{diff} represent CH₄ inputs from the ditch soil by ebullition and diffusion, respectively, and R_{MOX} represents CH₄ consumption by oxidation in the ditch water. The formulations of R_{MG} , R_{ebul} , R_{diff} and R_{MOX} are provided in Eqs. (S4)–(S8) in the Supplementary.

The CH₄ input associated with lateral drainage is separated into contributions from the unsaturated and the saturated peat soil columns (**Fig 1**):

$$R_{drain} = R_{du} + R_{ds}, \quad (6)$$

where R_{du} and R_{ds} [g CH₄ m⁻³ water s⁻¹] denote dCH_4 inputs associated with the drainage input from the unsaturated and the saturated parts of the adjacent peat, respectively.

Methane transport from the unsaturated peat is calculated as:

$$R_{du} = \frac{1}{V^t \Delta t} \sum_i^{unsat.layers} [CH_4]_{du,i}^{sw} \times F_{du,i}, \quad (7)$$

where V^t [m³] is the ditch-water volume at the end of the model time step, as calculated from the water balance in Section 2.2, and Δt [s] is the model time step. $[CH_4]_{du,i}^{sw}$ [g CH₄ m⁻³ water] is the dCH_4 concentration in the soil water of unsaturated layer i , calculated from the CH₄ concentration in soil pore air using the Bunsen solubility coefficient for CH₄ (B_{CH_4} =0.043), and $F_{du,i}$ [m³] is the water volume drained from that unsaturated layer during the model time step.



Methane transport from the saturated peat is calculated as:

$$R_{ds} = \frac{1}{V \Delta t} \sum_j^{sat.layers} [CH_4]_{ds,j}^{sw} \times F_{ds,j}, \quad (8)$$

230 where $[CH_4]_{ds,j}^{sw}$ [g CH₄ m⁻³ water] represents the dCH_4 concentration associated with the drainage input from the saturated layer j , and $F_{ds,j}$ [m³] is the corresponding drainage volume obtained during the model time step. In the saturated peat, this concentration is derived from CH₄ stored in the peat pore space and is represented by dCH_4 in the pore water using the same Bunsen gas–water partitioning relationship as for the unsaturated peat.

2.5 Emissions of gases from the ditch to the atmosphere

235 Gas exchange of CO₂ and CH₄ across the ditch water–air interface is calculated from the concentration gradient between the ditch water and the atmosphere:

$$F_g = k_g \times (C_{aq} - C_{eq}) \times \Delta t, \quad (9)$$

where F_g [g gas m⁻² ditch] is the net gas transfer for one model time step, k_g [m s⁻¹] is the gas exchange velocity, C_{aq} [g m⁻³ water] is the dCO_2 or dCH_4 concentration in the ditch water (**Section 2.4**), and C_{eq} [g m⁻³ water] is the dissolved concentration in equilibrium with the atmosphere. C_{eq} is calculated from the atmospheric gas concentration using the corresponding Ostwald solubility coefficient. Fixed Ostwald solubility coefficients of 0.04 for CH₄ and 1.076 for CO₂ are used, representative of freshwater conditions at approximately 10 – 20°C. This CO₂ coefficient value has been defined for freshwater conditions and neglects explicit pH dependence. Positive values of F_g denote emission from the ditch to the atmosphere, whereas negative values of F_g denote atmospheric uptake by the ditch water. Atmospheric O₂ re-aeration of the ditch water is calculated using
 245 the same gas-exchange formulation.

To obtain the gas exchange velocity k_g for CH₄, we first estimated k_{600} (in m d⁻¹), the gas exchange velocity normalized to a Schmidt number of 600, corresponding approximately to CO₂ in freshwater at 20°C, using a regression equation from a meta-analysis of gas exchange rates in streams and small rivers (Raymond et al., 2012):

$$k_{600} = (VS)^{0.89} \times D^{0.54} \times 5037, \quad (10)$$

250 where V [m s⁻¹] is the ditch water velocity, S is the dimensionless ditch slope, set to 0.05 in the default configuration, D [m] is the ditch water depth.

The value of k_g for CH₄ at the ditch-water temperature T was then derived from k_{600} by:

$$k_g = k_{600} \times \left(\frac{600}{Sc_{CH_4}} \right)^n, \quad (11)$$



where Sc_{CH_4} is the Schmidt number for CH_4 at the ditch water temperature T . Given the direct solar exposure of the ditches, the ditch-water temperature T is estimated as the soil surface temperature plus a prescribed thermal offset of 0.5°C . The Schmidt-number exponent n is set to 0.6, within the typical range of $\frac{1}{3}$ for a flat water surface to $\frac{2}{3}$ for a wavy water surface. Similarly, the gas exchange velocity k_g for CO_2 can be calculated with Sc_{CO_2} using the same method. Freezing of the ditch-water column is not explicitly represented in the current model.

2.6 Sites and simulation protocol

We conducted idealized simulations of peatland drainage including ditches at 10 near-pristine peatland sites, following the same protocol as Liu et al. (2026a). Before imposing the ditch drainage, the model was calibrated under present-day climate conditions using site-observations of NEE and CH_4 emissions (Liu et al., 2026a). We then considered idealized virtual ditch-drainage scenarios in which the drainage target was set by lowering the site-specific baseline water table by 20, 50, and 80 cm, respectively. These target values represent prescribed drawdown offsets relative to the baseline water table, rather than fixed water-table depths, and the simulated water table remains dynamic and varies with rainfall and other water-balance processes. Site descriptions and detailed protocols, including model calibration and water-table baseline determination, are described in Liu et al. (2026a). In each drainage scenario, the ditch depth was prescribed as part of the idealized ditch geometry to keep the ditch bottom below the intended drainage level. The prescribed ditch depth was then used as the vertical reference for converting the simulated ditch-water depth (D) to the ditch WTD below the local peat surface.

3 Results

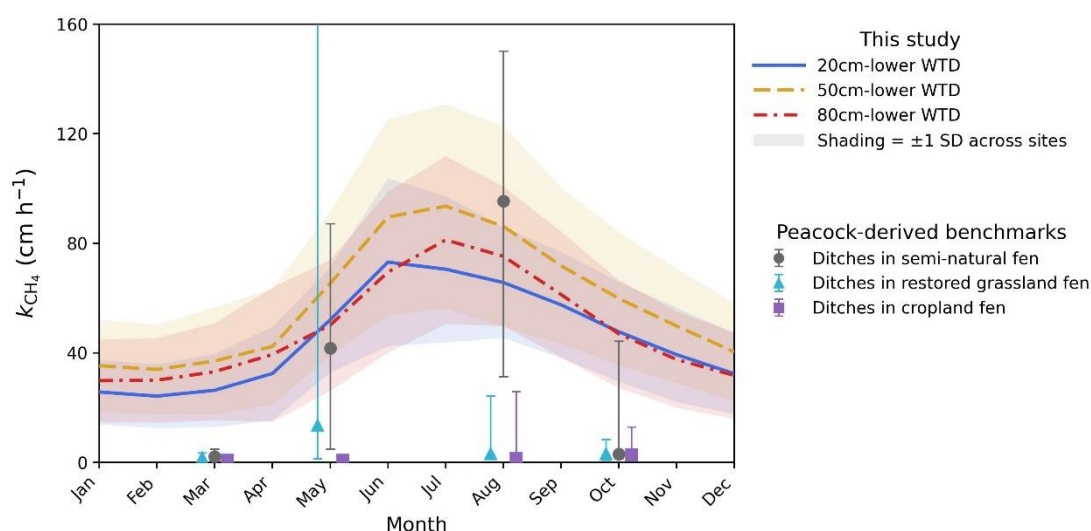
3.1 Gas exchange velocity

To our knowledge, few studies reported gas exchange velocities for peatland ditches. Among the available studies, Peacock et al. (2017) is the only one we found that reported sufficient information to derive CH_4 gas exchange velocity (k_{CH_4}) from measured ditch CH_4 fluxes and dCH_4 concentrations for semi-natural fen, restored grassland fen, and cropland fen ditches. Because our simulations represent near-pristine peatlands subject to idealized drainage, we used Peacock-derived k_{CH_4} values for semi-natural fen ditches as the main observational benchmark for comparing the magnitude and seasonality of simulated ditch gas-exchange velocity, rather than for site-specific validation (Fig. 4 and Fig. S1).

Simulated k_{CH_4} showed a clear seasonal cycle at each of the 10 peatland sites, with lower values in winter and early spring and higher values during the warm season. This seasonal pattern is associated with the ditch hydrological response described in Section 3.2, which affects the water velocity V and water depth D used to calculate k_{600} (Eq. 10). In May, mean simulated k_{CH_4} ranged from 50.2 to 65.4 cm h^{-1} for the three drainage scenarios, while the Peacock-derived semi-natural-fen benchmark has a median of 41.8 cm h^{-1} . In August, simulated means ranged from 65.7 to 86.3 cm h^{-1} , alongside a Peacock-derived median of 95.4 cm h^{-1} . Simulated k_{CH_4} is also lower during the colder months than during the warm season, consistent with the seasonal



pattern indicated by the Peacock-derived values. However, simulated colder-season values remained substantially higher in
 285 magnitude, with mean values of 26.4–37.1 cm h⁻¹ in March and 47.0–59.9 cm h⁻¹ in October, whereas the corresponding
 Peacock-derived medians were 2.1 and 3.1 cm h⁻¹, respectively. Site-level seasonal patterns showed substantial variation in
 both magnitude and timing of peak k_{CH_4} for each site (**Fig. S1**).



290 **Figure 4. Seasonal variation in simulated CH₄ gas exchange velocity (k_{CH_4} , cm h⁻¹) in ditches compared with literature-derived benchmarks.** Lines show mean simulated k_{CH_4} for the 10 peatland sites for each drainage scenario, and shading indicates ± 1 SD across 10 sites. Symbols show k_{CH_4} values derived by Peacock et al. (2017) for semi-natural fen (gray), restored grassland fen (cyan), and cropland fen (purple) ditches; vertical bars indicate the interquartile range. The semi-natural-fen values are used as the primary observational benchmark because the simulations represent near-pristine peatlands under idealized drainage. Peacock-derived values are available for
 295 March, May, August, and October.

3.2 Ditch hydrological response

The simulated ditch-water depth (D) varies seasonally and among sites under the three drainage intensity levels (**Fig. S2**). The 20-, 50-, and 80-cm lower- target WTD scenarios refer to prescribed lowering of the peat water table relative to the site-specific baseline peat WTD and therefore do not directly prescribe the ditch water level.

300 To express the simulated ditch water level relative to the local peat surface, the ditch WTD is calculated as $h - D$, where h is the ditch depth and D is the ditch-water depth (**Fig. 2**). Seasonal patterns for four representative sites are shown in **Fig. 5**, with results for all 10 sites provided in **Fig. S3**. For all the sites and months, the ditch WTD ranged from 6.7–32.4, 32.1–64.9, and 67.8–90.2 cm below the local peat surface for the 20-, 50-, and 80-cm lower-WTD scenarios, respectively (**Fig. S3**). The seasonal amplitude of the ditch WTD tends to decrease with stronger drainage, with median amplitudes of 11.7, 10.3, and 6.6
 305 cm for all sites for the three scenarios, respectively.

The ditch discharge (F_{out}) also varies seasonally among sites, ranging from 0.008–0.137, 0.010–0.172, and 0.021–0.134 m³ day⁻¹ m⁻¹ of ditch under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively (**Figs. 5 and S3**). The site-level mean F_{out}

generally increased from the 20- to the 50-cm lower-WTD scenario, with the across-site median increasing from 0.094 to 0.136 $\text{m}^3 \text{ day}^{-1} \text{ m}^{-1}$ of ditch. The median site-level relative increase was 45.8%. Further drainage to 80 cm of depth produced no
 310 consistent additional increase in discharge.

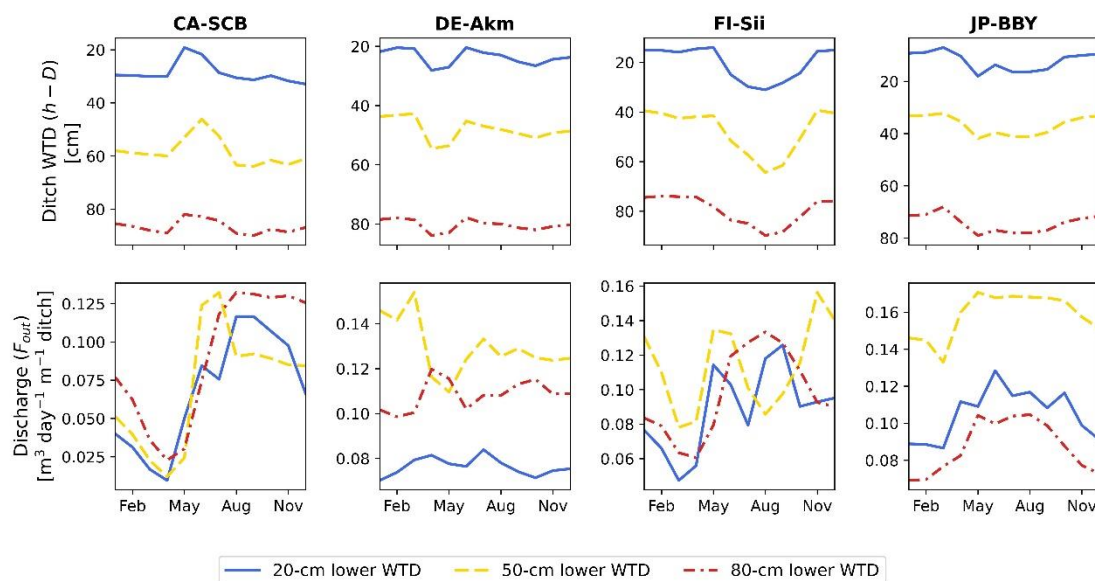


Figure 5. Seasonal variation in simulated ditch-water-table depth and discharge for four representative sites under the three drainage scenarios. The upper row shows the ditch water-table depth below the local peat surface, calculated as $h - D$, where h is the ditch depth and D is the ditch-water depth (Fig. 2). The lower row shows the ditch discharge F_{out} . Lines represent the 20-, 50-, and 80-cm lower-WTD drainage scenarios. Monthly values represent the mean seasonal cycle for the 5-year period starting 20 years after drainage initiation. Results for all 10 sites are shown in Fig. S3.

The discharge-component analysis showed that drainage from unsaturated peat (F_{du}) was the dominant contribution to F_{out} across all sites and drainage scenarios (Figs. 6 and S4). Its median contribution was 92.3%, 94.2%, and 93.8% under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively. In comparison, the rainfall input (F_{pre}), the saturated-soil drainage (F_{ds}),
 320 and the water carried over from the previous timestep each contributed only about 1-3% of the total ditch discharge.

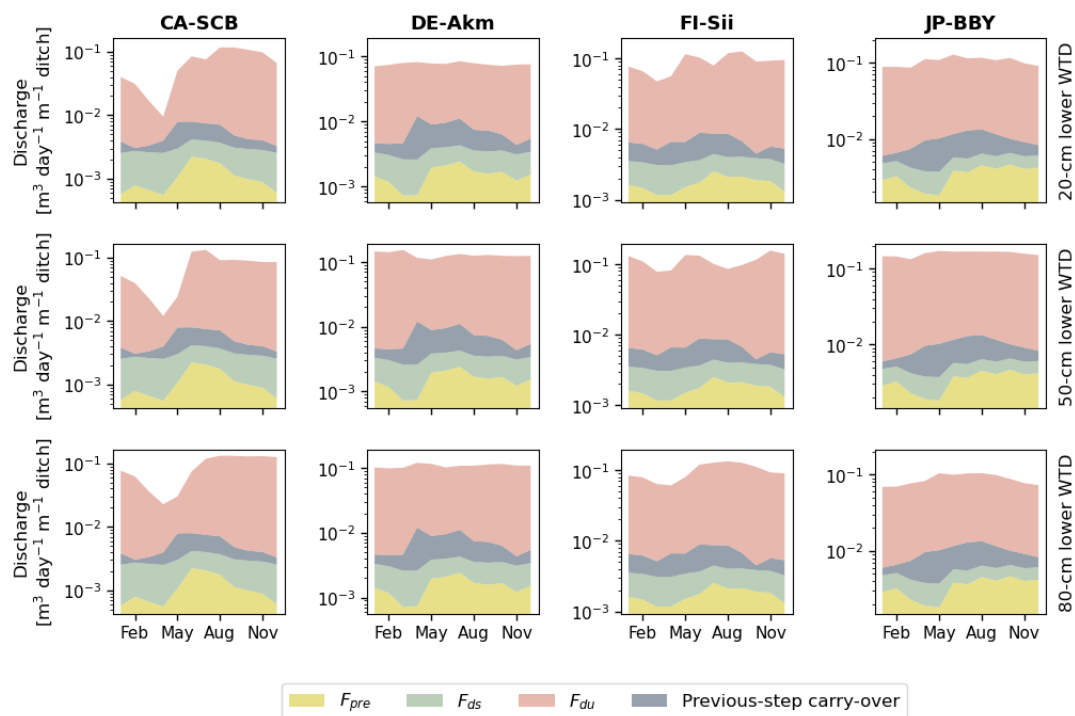


Figure 6. Seasonal contributions to the simulated ditch discharge (F_{out}) for four representative sites under the three drainage scenarios. Rows correspond to the 20, 50, and 80 cm lower-WTD drainage scenarios, and columns correspond to the four representative peatland sites. Colors show the discharge components defined in Section 2.2 and Fig. 2: the rainfall input (F_{pre}), the saturated-soil drainage (F_{ds}), the unsaturated-soil drainage (F_{du}), and the water carried over from the previous timestep. Values are monthly means expressed per unit ditch length in $\text{m}^3 \text{ day}^{-1} \text{ m}^{-1}$ of ditch. Results for all 10 sites are shown in Fig. S4.

3.3 Ditch carbon fluxes and DOC concentrations

The simulated ditch CH_4 and CO_2 fluxes and ditch DOC concentrations are averaged over a 5-year period starting 20 years after drainage initiation. Net fluxes and DOC concentrations are shown in **Fig. 7**, the corresponding component fluxes in **Fig. 8**, and site-level results and temporal variations are in **Figs. S5–S7**.

Simulated ditch CH_4 emissions vary substantially for all sites but consistently decrease with stronger drainage. Across the 10 sites ($n=10$), median emissions decreased from $0.13 \text{ g CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ under the 20-cm lower-WTD scenario to 0.10 and $0.09 \text{ g CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ under the 50- and 80-cm scenarios, respectively (**Fig. 7a**). The simulated median CH_4 emissions are broadly consistent in magnitude with field measurements from Peacock et al. (2017) for fen ditches at different sites and with meta-analysis estimates reported by Gan et al. (2024) (**Fig. 7a**). At the site level, CH_4 emissions are near zero at CA-SCB and FI-Sii, where mean fluxes ranged from 0.001 to $0.009 \text{ g CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ for all drainage scenarios (**Fig. S5**). This primarily reflects the comparatively low CH_4 inputs to the ditch water at these two sites (**Fig. S6**). At the remaining sites, simulated CH_4 emissions are generally within the range of these field and meta-analysis benchmarks (**Fig. S5**).

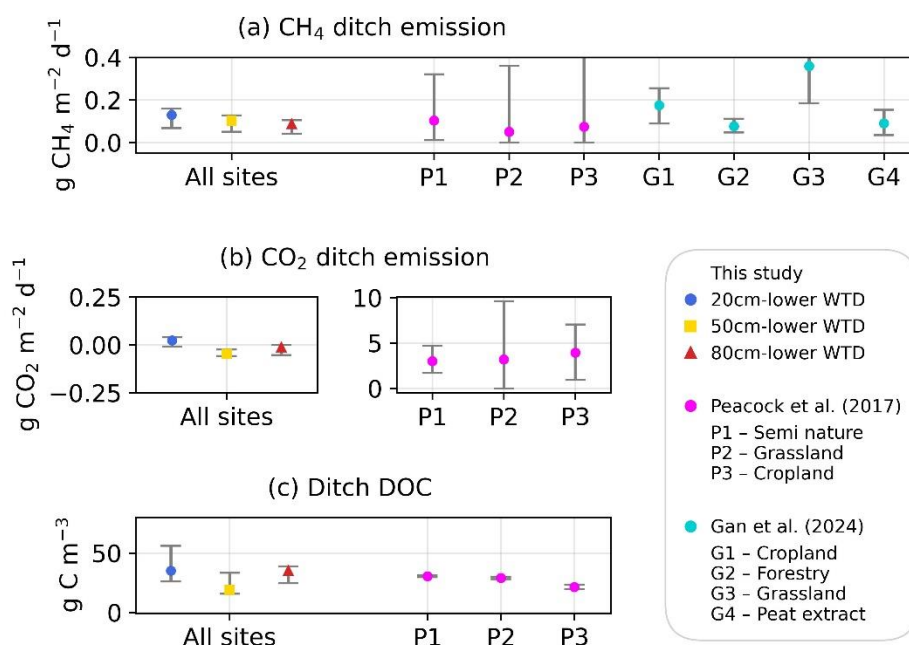


Figure 7. Simulated ditch CH₄ and CO₂ fluxes and dissolved organic carbon (DOC) concentrations. Symbols show medians aggregated for the 10 peatland sites and for the 20-, 50-, and 80-cm lower-WTD drainage scenarios, and error bars indicate the interquartile range. Field measurements from Peacock et al. (2017) and meta-analysis estimates from Gan et al. (2024) are shown as observational context. Corresponding site-level results are shown in Figs. S5-S7.

The CH₄ component fluxes show that CH₄ transported from the saturated-soil drainage (R_{ds}) is the dominant positive input, with median fluxes of 0.12, 0.10, and 0.09 g CH₄ m⁻² d⁻¹ under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively (Fig. 8a). Ebullitive CH₄ transfer from the ditch soil to the ditch water (R_{ebul}) was the second-largest input to the ditch-water CH₄ pool, with median fluxes of 0.019, 0.008, and 0.006 g CH₄ m⁻² d⁻¹, respectively. In comparison, CH₄ transported from the unsaturated-soil drainage (R_{du}), from methanogenesis in the ditch water (R_{MG}), and the net diffusion from the ditch soil (R_{diff}) are smaller. CH₄ oxidation in the ditch water (R_{MOX}) is a consistent loss, with median fluxes of -0.037, -0.029, and -0.024 g CH₄ m⁻² d⁻¹ under the 20-, 50-, and 80-cm scenarios, respectively. With stronger drainage, CH₄ inputs from the saturated-soil drainage and ebullitive transfer from the ditch soil to the ditch water decreased, whereas in-ditch methanogenesis remained small (Fig. 8a; Fig. S6).

Direct observations of peatland-ditch CO₂ fluxes remain scarce, but Peacock et al. (2017) reported fen-ditch fluxes exceeding 3 g CO₂ m⁻² d⁻¹. Because lateral dCO_2 transport from adjacent peat is not represented in the model (Section 2.1), these observations are shown only as observational context rather than for direct model evaluation. Median simulated CO₂ fluxes are 0.023, -0.047, and -0.013 g CO₂ m⁻² d⁻¹ under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively (Fig. 7b). Negative mean CO₂ fluxes occur at 3 of 10 sites under the 20-cm scenario and at 8 of 10 sites under both the 50- and 80-cm scenarios (Fig. S5). Despite the small or negative net ditch-atmosphere fluxes, all simulated CO₂ production components are positive (Fig. 8b). CH₄ oxidation in the ditch water (MOX_{water}) is by far the largest CO₂ production term, with median fluxes



of 0.10, 0.08, and 0.07 g CO₂ m⁻² d⁻¹ under the three scenarios, respectively. The DOC respiration ($Resp_{DOC}$) contributes to median fluxes of 0.007, 0.003, and 0.002 g CO₂ m⁻² d⁻¹, while the SOC respiration ($Resp_{SOC}$) and CH₄ oxidation in the ditch soil (MOX_{soil}) remain small (Figs. 8b, S7).

Median ditch-water DOC concentrations are 44.0, 24.1, and 33.3 g C m⁻³ under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively (Fig. 7c). These values are broadly comparable with the ditch-water DOC concentrations reported by Peacock et al. (2017), which ranged from 21.5 to 30.6 g C m⁻³. DOC concentrations decrease between the 20- and the 50-cm scenario, with a median site-level reduction of 42.5%, whereas the response under the 80-cm scenario varies among sites and shows no systematic further decrease relative to the 20-cm scenario. At the site level, DOC concentrations vary substantially, spanning 20.0–87.5, 13.3–41.9, and 20.0–47.2 g C m⁻³ under the three scenarios, respectively (Fig. S5).

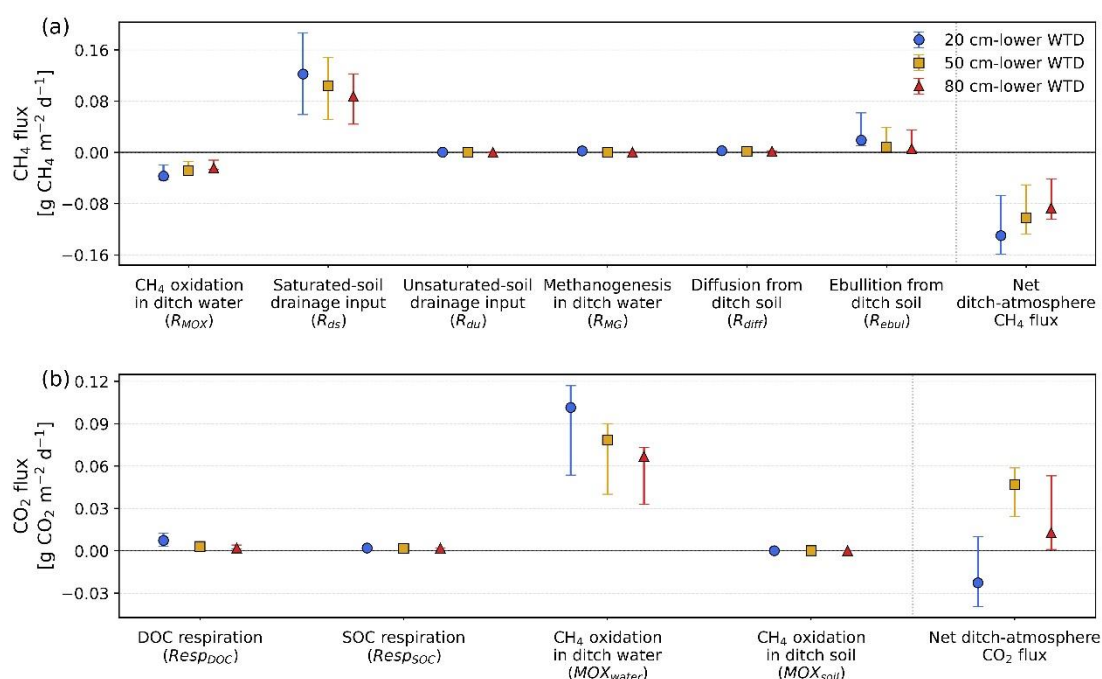


Figure 8. CH₄ component fluxes and CO₂ production and exchange under different drainage scenarios. (a) CH₄ component fluxes, including CH₄ oxidation in the ditch water (R_{MOX}), CH₄ inputs from saturated- and unsaturated-soil drainage (R_{ds} and R_{du}), methanogenesis in the ditch water (R_{MG}), diffusion from the ditch soil (R_{diff}), and the ebullition from the ditch soil (R_{ebul}), and CH₄ loss to the atmosphere. Positive values indicate CH₄ inputs to the ditch water, whereas negative values indicate CH₄ losses. (b) CO₂ production fluxes from the DOC respiration ($Resp_{DOC}$), the SOC respiration ($Resp_{SOC}$), CH₄ oxidation in the ditch water (MOX_{water}), and CH₄ oxidation in the ditch soil (MOX_{soil}), together with CO₂ exchange with the atmosphere. For atmospheric CO₂ exchange, positive values indicate input from the atmosphere to the ditch water, whereas negative values indicate loss to the atmosphere. Symbols show medians and error bars indicate the interquartile range. Corresponding site-level temporal variations are shown in Figs. S6 and S7.

3.4 Ditch effects

To quantify the extent to which ditch CH₄ emissions offset the drainage-induced reduction in terrestrial peat CH₄ emissions, we compared the CH₄ emission reduction calculated with and without accounting for ditch emissions, following Gan et al. (2024):



$$offset = \frac{(\Delta CH_{4,exclude} - \Delta CH_{4,include})}{\Delta CH_{4,exclude}} \times 100\%, \quad (12)$$

where $\Delta CH_{4,exclude}$ is the drainage-induced CH_4 emission reduction calculated from terrestrial peat emissions alone, and $\Delta CH_{4,include}$ is the corresponding reduction after including terrestrial and ditch CH_4 emissions weighted by their respective area fractions.

The simulated offsets are higher under shallower drainage, with a median of 12.7%, 8.1% and 7.2% under the 20-, 50- and 80-cm lower-WTD scenarios, respectively (**Fig. 9**). For comparison, Peacock et al. (2021) reported an offset of 18%, while Gan et al. (2024) estimated offsets ranging from 6% to 27% for different types of drainage ditches.

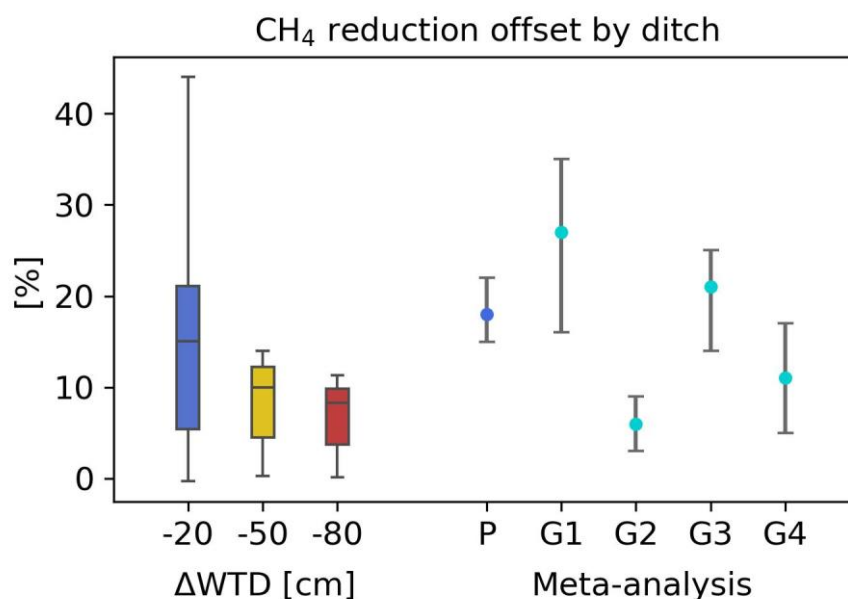


Figure 9. Percentage of the drainage-induced terrestrial peat CH_4 emission reduction offset by ditch CH_4 emissions. Boxplots show simulated offsets under the three drainage scenarios. Points with error bars represent meta-analysis values for comparison: blue point from Peacock et al. (2021) and cyan points from Gan et al. (2024) (G1 - Cropland, G2 - Forestry, G3 - Grassland, G4 - Peat extract).

4. Discussion

Our study presents a new parameterization for modelling ditch emissions from drained peatlands, though several simplifications and limitations must be acknowledged. Our modelling approach, while providing valuable insights, remains relatively simple and incorporates numerous assumptions that may not fully capture the complexity of real-world ditch systems.

The simulations show that ditch CH_4 emissions are controlled mainly by CH_4 supplied from the adjacent peat rather than by methanogenesis within the ditch water. This concurs with empirical findings from natural headwater streams draining boreal peatlands (Taillardat et al., 2022). Similarly, empirical work showed that CH_4 emissions from drainage canals in tropical peatlands are largely sustained by lateral inflows from the drained peat (Somers et al., 2023).



The saturated-soil drainage is the dominant positive CH_4 input, followed by the ebullition from the ditch soil, whereas the unsaturated-soil drainage, in-ditch methanogenesis, and the diffusion from the ditch soil are comparatively smaller (**Fig. 8a**). Both saturated-soil CH_4 input and ebullition decrease with stronger drainage, which is consistent with the decline in median ditch CH_4 emissions from 0.130 to 0.102 and 0.087 $\text{g CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively. Consequently, ditch CH_4 emissions offset by 12.7%, 8.1%, and 7.2% of the drainage-induced reduction in terrestrial peat CH_4 emissions under the three scenarios. These results indicate that ditch emissions partly offset, but do not fully counteract, the drainage-induced reduction in terrestrial peat CH_4 emissions.

One limitation lies in our assumption of perfect rectangular ditch geometries. In reality, drainage ditches often have more complex cross-sectional profiles, typically trapezoidal or “V” shapes with sloped sides. This geometric simplification may influence the estimation of water volume in the ditch or the movement of carbon between the DOC and the SOC pools. Furthermore, our model assumes completely bare ditch surfaces. However, grasses and other vegetation can establish along ditch side slopes. Such vegetation can provide additional litter-derived substrates for CH_4 production and modify local biogeochemical conditions. Emergent wetland plants possess a spongy tissue called aerenchyma, which can provide an additional pathway for methane transport from the root zone to the atmosphere while simultaneously facilitating root-zone oxygenation, thereby potentially suppressing methanogenesis. Our simulations also do not account for ditch maintenance activities, such as periodic deepening to counteract peatland subsidence.

A major limitation arises from the representation of CO_2 in the terrestrial soil and ditch modules. In the standard ORCHIDEE-PEAT soil carbon scheme, CO_2 produced by SOC decomposition is directly included in soil respiration, and no explicit $d\text{CO}_2$ pool is represented in peat soil water. Consequently, unlike CH_4 , no $d\text{CO}_2$ is transported laterally from the adjacent peat to the ditch with drainage water. The ditch module nevertheless represents $d\text{CO}_2$ in the water column for air–water gas exchange. Drainage therefore adds water to the ditch without a corresponding $d\text{CO}_2$ input from the surrounding peat, which can dilute ditch-water CO_2 concentrations and, when concentrations fall below atmospheric equilibrium, produce negative net ditch–atmosphere CO_2 fluxes. This model structure is consistent with the very small or negative CO_2 fluxes simulated here despite positive CO_2 production components within the ditch (**Figs. 8, and S7**). Simulated ditch CO_2 exchange should therefore be interpreted cautiously, and future model development should include an explicit representation of $d\text{CO}_2$ transport with drainage water if ditch CO_2 fluxes are to be evaluated quantitatively.

While atmospheric CH_4 exchange is represented through diffusive transfer across the air–water interface, real ditch systems may also emit CH_4 through direct ebullition to the atmosphere and plant-mediated transport through emergent vegetation. In the current model, ebullition is represented only as CH_4 transfer from the ditch soil to the ditch water, rather than as a direct soil-to-atmosphere emission pathway. We defined default parameter values to achieve simulated diffusive CH_4 fluxes within the range of published meta-analysis data. When additional emission pathways are incorporated into the future model, these parameter values will require adjustment to maintain realistic total flux estimates.

Despite these limitations, simulated ditch CH_4 emissions were generally within the range of the available field measurements and meta-analysis estimates, supporting the overall magnitude of the simulated CH_4 fluxes. However, the structural limitation



in dCO_2 transport prevents a robust quantitative assessment of ditch CO_2 exchange and therefore limits assessment of the net greenhouse-gas impact, such as CO_2 -equivalent emissions, of drainage ditch networks relative to undrained peatland conditions.

5. Conclusion

440 We have developed a physical parameterization of ditch hydrology and emission processes within the ORCHIDEE-PEAT model to simulate CO_2 and CH_4 emissions from drainage ditches in peatlands. Key components include carbon allocation to new DOC and SOC pools within ditches, ditch discharge calculations, gas exchange velocity parameterization, and diffusive gas emission across the air-water interface. The simulated CH_4 gas exchange velocities for CH_4 fall within the range of available field-derived estimates. Modelled CH_4 emissions from ditches are generally within the range of available field
445 observations and meta-analysis estimates, demonstrating the model's potential to reproduce observed emission magnitudes, although only the diffusive pathway was considered. Methane emission from the ditch can offset 7.2-12.7% drainage-induced reduction in terrestrial peat CH_4 emissions. Simulated ditch CO_2 fluxes were small or negative, but these values cannot be interpreted quantitatively because an explicit dCO_2 pool in peat soil and its lateral transport with drainage water are not represented in the current model formulation. This technical development can contribute to peatland drainage impact
450 assessments by enabling the simulation of ditch emissions alongside terrestrial soil emissions. Future work should incorporate direct ebullitive CH_4 emissions to the atmosphere and plant-mediated CH_4 transport, together with an explicit representation of dCO_2 transport with drainage water. Moreover, more realistic representations of ditch characteristics and management practices are needed. Nevertheless, this work provides a basis for integrated assessment of both terrestrial and aquatic carbon fluxes in drained peatlands.



455 **Code and data availability**

The ORCHIDEE-PEAT_Ditch model (r9703) code used in this study is open-source and distributed under the CeCILL (CEA CNRS INRIA Logiciel Libre) license. It is deposited at https://forge.ipsl.fr/orchidee/wiki/GroupActivities/CodeAvalaibilityPublication/ORCHIDEE-PEAT_Ditch (last access: 16 September 2026) and archived at <https://doi.org/10.5281/zenodo.22879175> (Liu, 2026b), with guidance to install and run the
460 model at <https://forge.ipsl.jussieu.fr/orchidee/wiki/Documentation/UserGuide> (last access: 16 September 2026). The data supporting this study is available at <https://doi.org/10.5281/zenodo.22879175> (Liu, 2026b).

Author contributions

PC contributed to conceptualization and study design. LL and THN contributed to methodology, software development, model simulations, formal analysis, visualization, and writing of the original draft. CQ, YX, and ES contributed to methodology,
465 model development and configuration, and interpretation of the results. YS and RL contributed to interpretation and discussion of the results. All authors contributed to writing – review and editing and approved the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Review statement

- 480 The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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