

Supplement to

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

This Supplement includes:

Supplementary text,

Supplementary figures (Fig.S1 - S7).

Supplementary text

This supplementary text presents the fundamental equations governing the biogeochemical processes that influence CO₂ and CH₄ concentrations in the ditch water. These equations are adapted from peat soil simulations described in detail by Qiu et al. (2018) and Salmon et al. (2022).

Oxic decomposition:

The amount of carbon per volume unit that undergoes oxic decomposition (dC_{oxic} in g C m⁻³ water) in a time step, limited by the availability of oxygen in water, is:

$$dC_{oxic} = \min\left([C] \frac{\Delta t}{\tau}, [O_2] \frac{M_C}{M_{O_2}}\right), \quad (S1)$$

where $[C]$ [g C m⁻³ water] is the carbon concentration in the organic carbon pool undergoing decomposition, $[O_2]$ [g O₂ m⁻³ water] is the oxygen concentration in the ditch water, Δt [s] is the model time step, and τ [s] is the residence time of the corresponding carbon pool. M_C and M_{O_2} are the molar masses of carbon and oxygen, respectively.

The corresponding amount of CO₂ produced per unit water volume over one model time step (dCO_2 in g CO₂ m⁻³ water) is calculated as:

$$dCO_2 = dC_{oxic} \frac{M_{CO_2}}{M_C} F_{CO_2}, \quad (S2)$$

where M_{CO_2} and M_C are the molar masses of CO₂ and carbon, respectively, and F_{CO_2} is the fraction of decomposed carbon released as CO₂. The remaining fraction is transferred to other organic carbon pools.

Anoxic decomposition (i.e. methanogenesis):

The amount of carbon per volume unit that undergoes anoxic decomposition (dC_{MG} in g C m⁻³ water) over a time step is:

$$dC_{MG} = [C] k_{MG} e^{-[O_2]_p/[O_2]_{anoxia}} \Delta t, \quad (S3)$$

where $[C]$ [g C m⁻³ water] is the carbon concentration in the organic carbon pool undergoing decomposition, k_{MG} [s⁻¹] is the methanogenesis rate constant, $[O_2]_p$ [g O₂ m⁻³ water] is the dissolved oxygen concentration in the ditch water, $[O_2]_{anoxia}$ [g O₂ m⁻³ water] is the oxygen concentration at which anoxic conditions are reached and methanogenesis is enabled, and Δt [s] is the model time step.

The corresponding rate of change in CH₄ concentration (R_{MG} in g CH₄ m⁻³ s⁻¹) is:

$$R_{MG} = \frac{dC_{MG}}{\Delta t} \frac{M_{CH_4}}{M_C} F_{CH_4}, \quad (S4)$$

where M_{CH_4} and M_C are the molar masses of CH₄ and carbon, respectively, and F_{CH_4} is the fraction of decomposed carbon converted to CH₄. The remaining fraction is transferred to other carbon pools.

Methane oxidation (MOX)

The rate of change in the ditch CH₄ concentration due to CH₄ oxidation (R_{MOX} in g CH₄ m⁻³ s⁻¹), limited by dissolved oxygen availability, is calculated by:

$$R_{MOX} = \min\left(k_{MT} [CH_4], k_{MT} \frac{1}{2} [O_2] \frac{M_{CH_4}}{M_{O_2}}\right), \quad (S5)$$

where k_{MT} [s⁻¹] is the rate of methanotrophy, retaining the same values as in the terrestrial soil methanotrophy simulation which is calibrated for the pre-drained period. $[CH_4]$ [g CH₄ m⁻³ water] and $[O_2]$ [g O₂ m⁻³ water] are the dissolved methane and oxygen concentrations in the ditch water,

respectively, with $\frac{1}{2}$ accounting for the stoichiometric mole ratio of CH_4 to O_2 . M_{CH_4} and M_{O_2} are the molar masses of CH_4 and oxygen, respectively.

Ebullition flux

The ebullition transports methane from deep layers upward, moving it sequentially from one layer to the next. The rate of change of the ditch CH_4 concentration due to ebullition from soil below the ditch (R_{ebul} in $\text{g CH}_4 \text{ m}^{-3} \text{ s}^{-1}$) is calculated from bubbles leaving the top soil layer:

$$R_{\text{ebul}} = k_{\text{ebul}} ([\text{CH}_4]_{\text{top soil}} - [\text{CH}_4]_{\text{ET}}) p_{\text{ebul}} \varepsilon \frac{\Delta z}{D}, \quad (\text{S6})$$

where k_{ebul} is the ebullition rate constant, set to 1 h^{-1} . $[\text{CH}_4]_{\text{top soil}}$ and $[\text{CH}_4]_{\text{ET}}$ [$\text{g CH}_4 \text{ m}^{-3} \text{ air}$] are the methane concentration in the uppermost ditch-soil layer and the ebullition threshold concentration, respectively, both expressed on an air-volume basis. The threshold depends on temperature, pressure, and the methane mixing ratio in the bubbles. The effective methane porosity, ε [$\text{m}^3 \text{ air m}^{-3} \text{ soil}$], accounts for methane in both air-filled and water-filled pores under the assumption of gas–water equilibrium (Khvorostyanov et al., 2008). It converts methane concentrations from an air-volume basis to a soil-volume basis. p_{ebul} is the dimensionless, soil-moisture-dependent probability of bubbles escaping a soil layer, Δz [m] is the thickness of the uppermost ditch-soil layer, and D [m] is the effective ditch-water depth.

Diffusion flux

Methane diffusion between soil layers is simulated using Fick's second law:

$$\frac{\partial [\text{CH}_4]}{\partial t} = K(z) \frac{\partial^2 [\text{CH}_4]}{\partial z^2}, \quad (\text{S7})$$

where $[\text{CH}_4]$ [$\text{g CH}_4 \text{ m}^{-3} \text{ soil}$] is the methane concentration in the ditch soil, t [s] is time, z [m] is soil depth, and $K(z)$ [$\text{m}^2 \text{ s}^{-1}$] is the methane diffusion coefficient at depth z . The upper boundary permits methane exchange between the uppermost ditch-soil layer and the overlying ditch water.

The change in total soil CH_4 content after solving the tridiagonal diffusion matrix gives the diffusion flux between the ditch soil and the ditch water (positive for flux from soil to water):

$$R_{\text{diff}} = \frac{1}{D \Delta t} \sum_{\text{soil layer}} \Delta z_i ([\text{CH}_4]_{i,\text{after}} - [\text{CH}_4]_{i,\text{before}}), \quad (\text{S8})$$

where D [m] is the effective ditch-water depth, Δt [s] is the model time step, and Δz_i [m] is the thickness of soil layer i . $[\text{CH}_4]_{i,\text{before}}$ and $[\text{CH}_4]_{i,\text{after}}$ [$\text{g CH}_4 \text{ m}^{-3} \text{ soil}$] are the methane concentrations in layer i before and after the diffusion calculation, respectively. The summation extends over all ditch-soil layers, and R_{diff} is expressed in $\text{g CH}_4 \text{ m}^{-3} \text{ water s}^{-1}$.

Supplementary figures

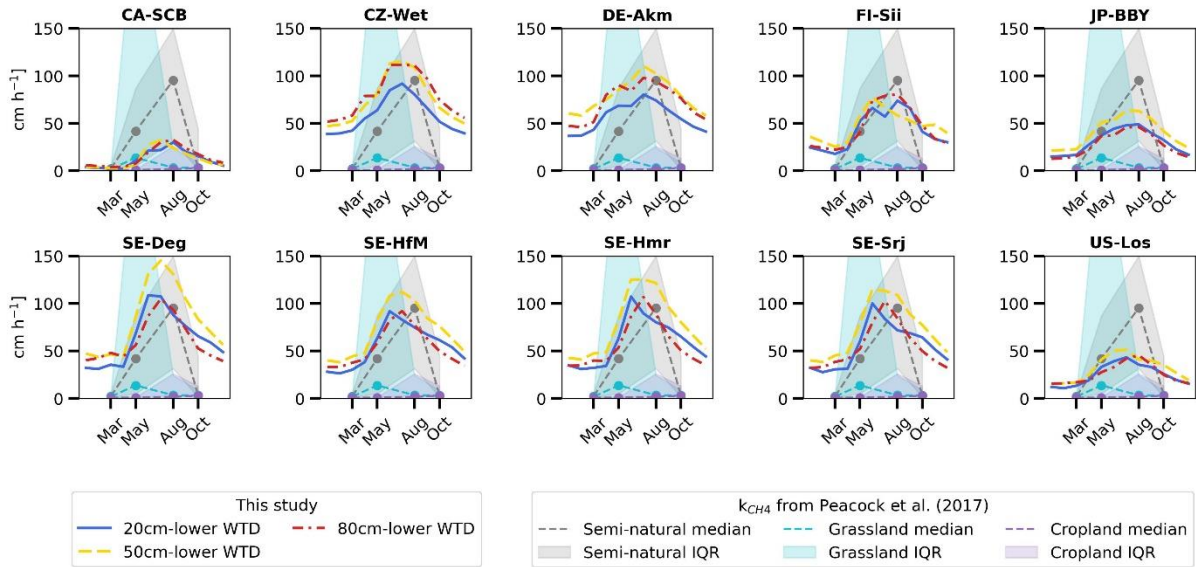


Figure S1. Site-level seasonal variation in simulated methane gas exchange velocity (k_{CH_4} , cm h^{-1}) compared with Peacock-derived benchmarks. Colored lines show monthly simulated results for the three drainage scenarios at each of the 10 peatland sites. Dashed lines and shaded ranges show the median and interquartile range of derived k_{CH_4} from Peacock et al. (2017) for semi-natural fen, restored grassland fen, and cropland fen ditches.

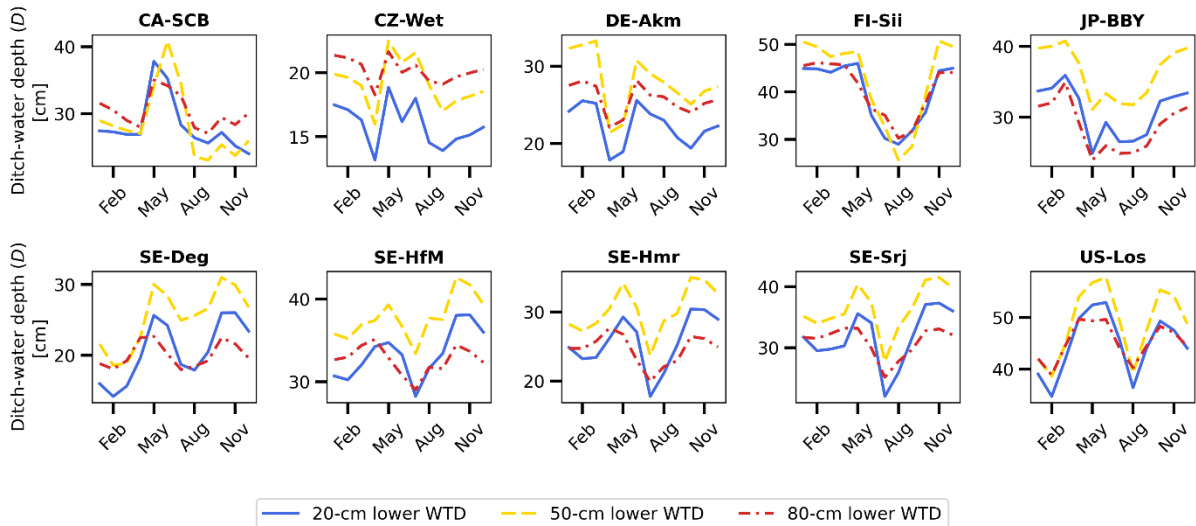


Figure S2. Site-level seasonal variation in simulated ditch-water depth (D) across drainage scenarios. Colored lines show the ditch-water depth for the 20-, 50-, and 80-cm lower-WTD drainage scenarios at each of the 10 peatland sites. Monthly values represent the mean seasonal cycle averaged over 5 years, starting 20 years after drainage initiation.

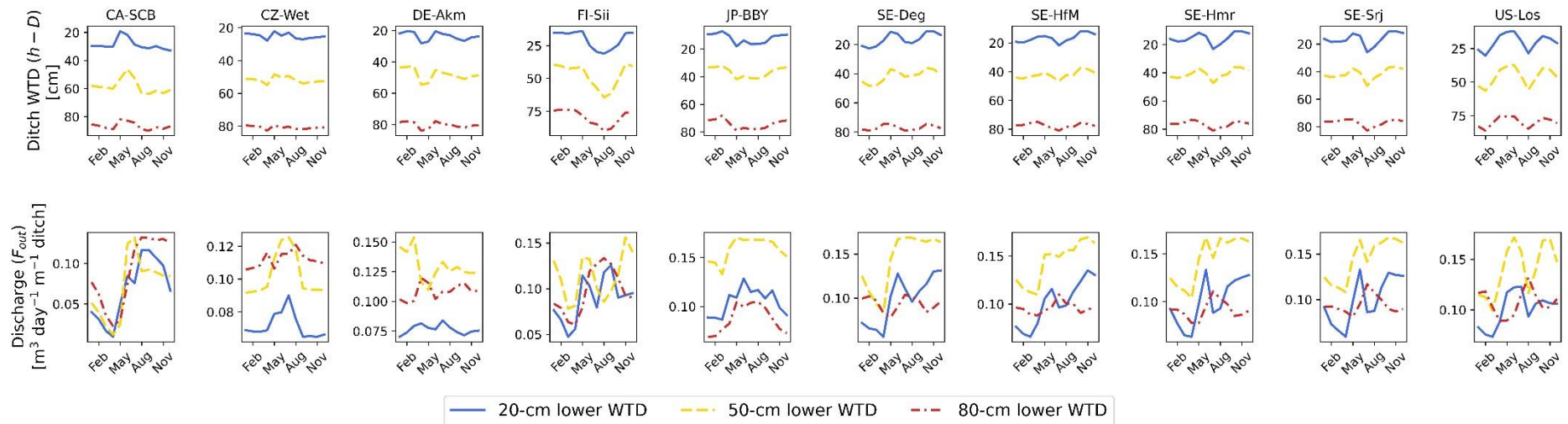


Figure S3. Seasonal variation in simulated ditch-water-table depth and discharge for all 10 sites under the three drainage scenarios. The upper row shows the ditch water-table depth below the local peat surface, calculated as $h - D$, where h is the ditch depth and D is the ditch-water depth (Fig. 2). 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.

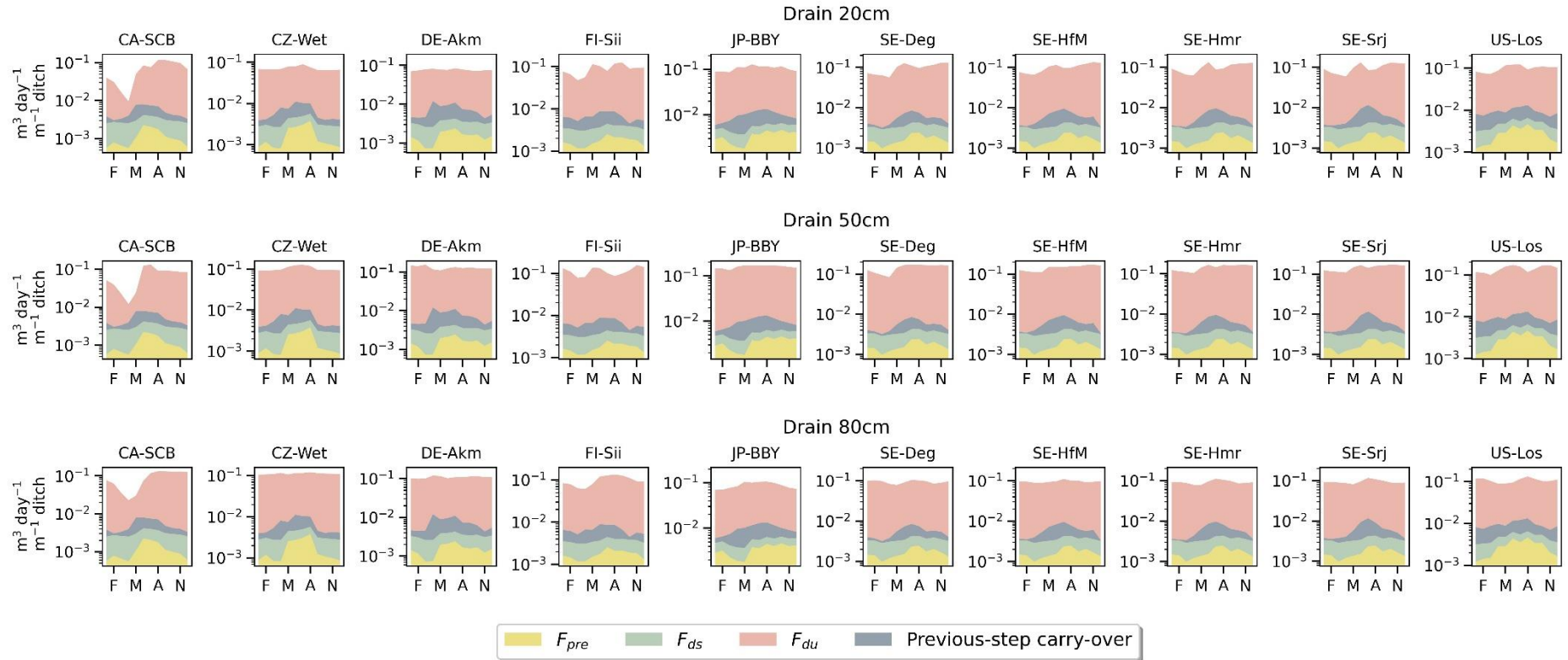


Figure S4. Seasonal contributions to simulated ditch discharge (F_{out}) for all 10 sites under the three drainage scenarios. Rows correspond to the 20, 50, and 80 cm lower-WTD drainage scenarios, and columns correspond to the 10 simulated peatland sites. Colors show the discharge components defined 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.

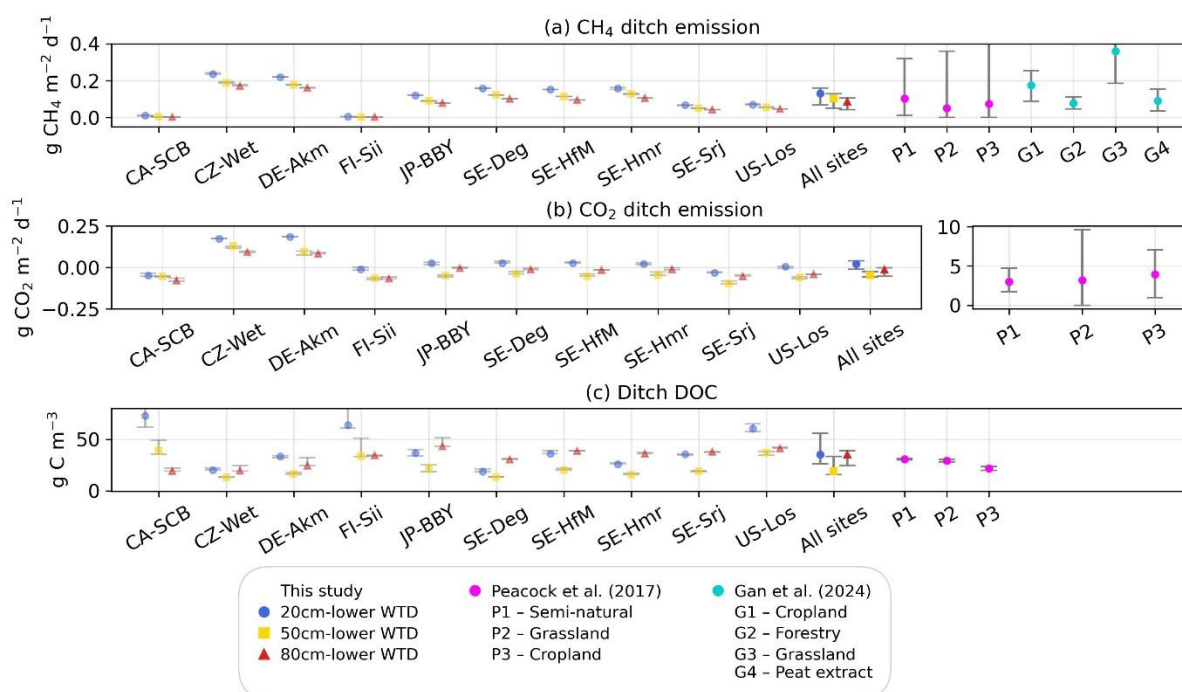


Figure S5. Site-level ditch CH₄ and CO₂ emissions and ditch-water DOC concentrations under different drainage scenarios. (a) Ditch CH₄ emissions, (b) ditch CO₂ emissions, and (c) ditch-water DOC concentrations. Field measurements from Peacock et al. (2017) and meta-analysis estimates from Gan et al. (2024) are shown as observational context.

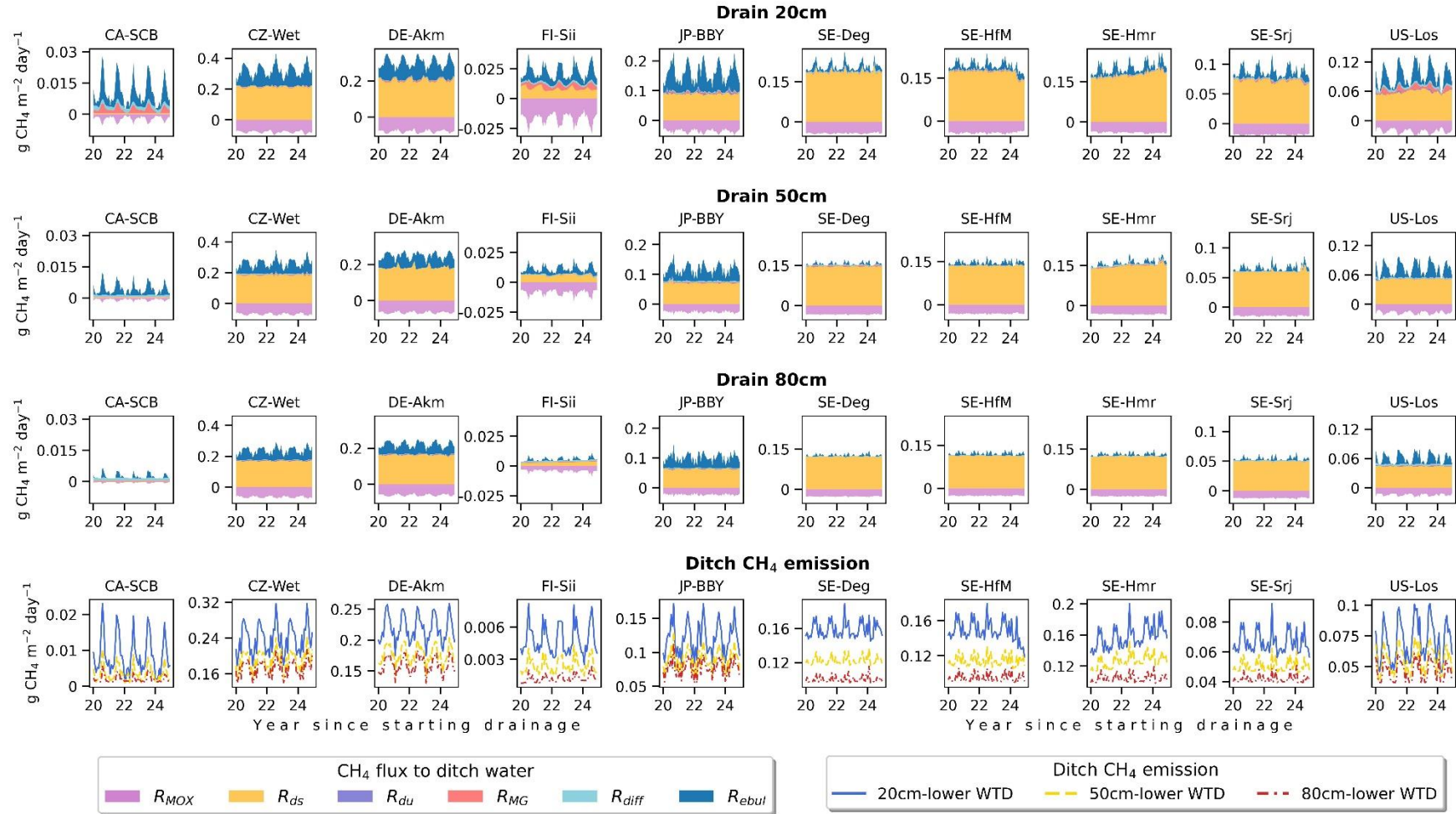


Figure S6. Site-level temporal variation in component fluxes of the ditch-water CH₄ balance under different drainage scenarios. The upper three rows show the CH₄ oxidation in the ditch water (R_{MOX}), CH₄ inputs associated with saturated- and unsaturated-peat drainage, methanogenesis in the ditch water (R_{MG}), diffusion from the ditch soil (R_{diff}), and the ebullition from the ditch soil (R_{ebul}) under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively. The two drainage-related CH₄ inputs from saturated soil (R_{ds}) and unsaturated soil (R_{du}) together constitute R_{drain} in Eq. (6). Positive values indicate transport of the CH₄ inputs to the ditch water, whereas negative values indicate CH₄ consumption or removal. The bottom row shows the corresponding net ditch CH₄ emissions to the atmosphere for the 5-year period starting 20 years after drainage initiation.

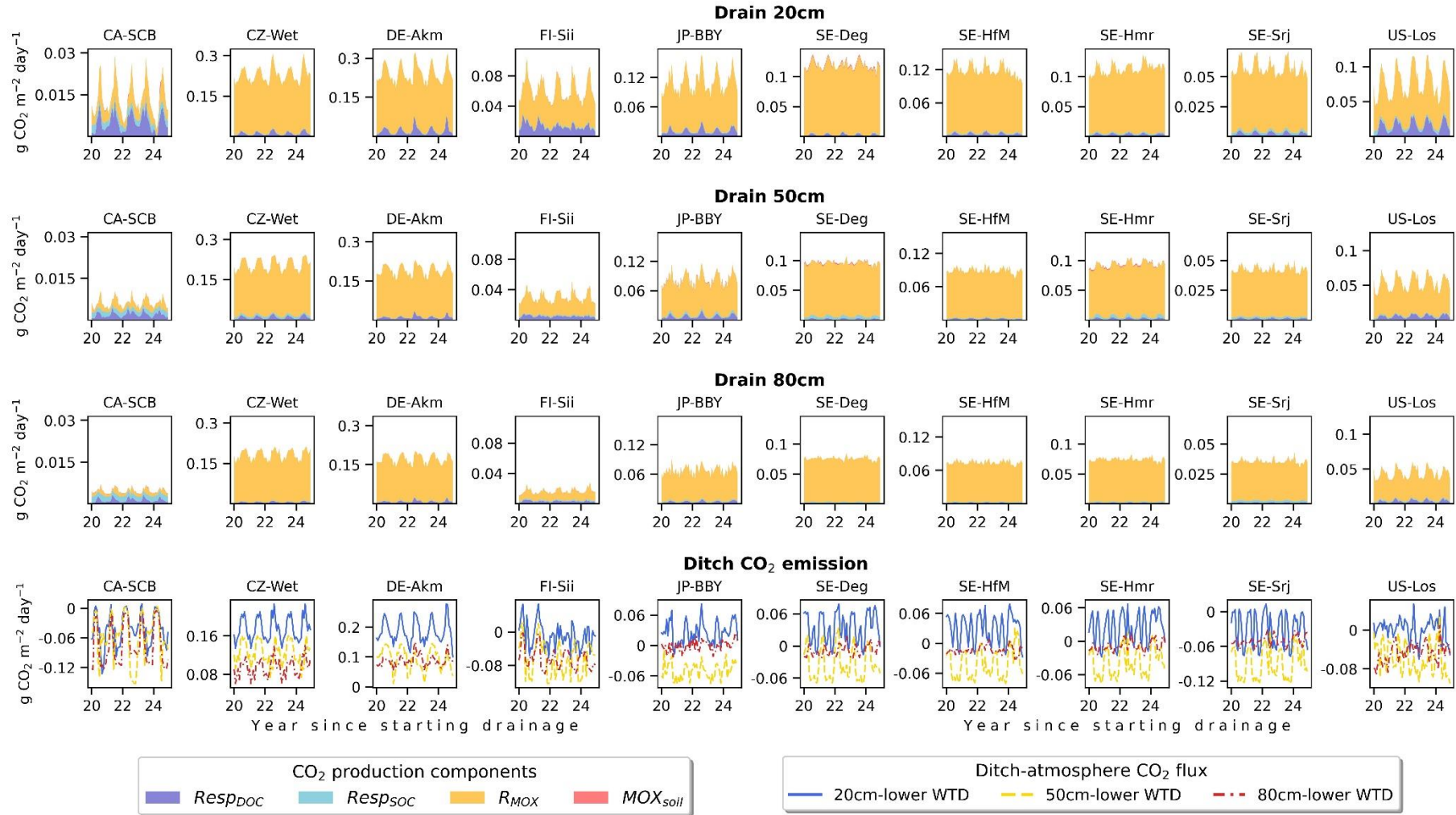


Figure S7. Site-level temporal variation in the ditch CO₂ production components and the net ditch–atmosphere CO₂ exchange for different drainage scenarios. The upper three rows show the CO₂ production from the DOC respiration ($Resp_{DOC}$), the SOC respiration ($Resp_{SOC}$), the CH₄ oxidation in the ditch water (MOX_{water}), and the CH₄ oxidation in the ditch soil (MOX_{soil}) under the 20-, 50-, and 80-cm lower-WTD scenarios, respectively. The bottom row shows the corresponding net ditch–atmosphere CO₂ fluxes, with positive values indicating CO₂ emission to the atmosphere and negative values indicating atmospheric CO₂ uptake by the ditch water. Values are shown for the 5-year period starting 20 years after drainage initiation.

References

- Gan, D., Zhang, Z., Li, H., Yu, D., Li, Z., Long, R., Niu, S., Zuo, H., Meng, X., Wang, J., and Ma, L.: Ditch emissions partially offset global reductions in methane emissions from peatland drainage, *Commun. Earth Environ.*, 5, 640, <https://doi.org/10.1038/s43247-024-01818-5>, 2024.
- Khvorostyanov, D. V., Krinner, G., Ciais, P., Heimann, M., and Zimov, S. A.: Vulnerability of permafrost carbon to global warming. Part I: model description and role of heat generated by organic matter decomposition, *Tellus B: Chemical and Physical Meteorology*, 60, 250, <https://doi.org/10.1111/j.1600-0889.2007.00333.x>, 2008.
- Peacock, M., Ridley, L. M., Evans, C. D., and Gauci, V.: Management effects on greenhouse gas dynamics in fen ditches, *Sci. Total Environ.*, 578, 601–612, <https://doi.org/10.1016/j.scitotenv.2016.11.005>, 2017.
- 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., Largeon, 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 CO₂, water, and energy fluxes on daily to annual scales, *Geosci. Model Dev.*, 11, 497–519, <https://doi.org/10.5194/gmd-11-497-2018>, 2018.
- Salmon, E., Jégou, F., Guenet, B., Jourdain, L., Qiu, C., Bastrikov, V., Guimbaud, C., Zhu, D., Ciais, P., Peylin, P., Gogo, S., Laggoun-Défarge, F., Aurela, M., Bret-Harte, M. S., Chen, J., Chojnicki, B. H., Chu, H., Edgar, C. W., Euskirchen, E. S., Flanagan, L. B., Fortuniak, K., Holl, D., Klatt, J., Kolle, O., Kowalska, N., Kutzbach, L., Lohila, A., Merbold, L., Pawlak, W., Sachs, T., and Ziemblińska, K.: Assessing methane emissions for northern peatlands in ORCHIDEE-PEAT revision 7020, *Geosci. Model Dev.*, 15, 2813–2838, <https://doi.org/10.5194/gmd-15-2813-2022>, 2022.