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Supplement of

Enhanced CO_2 emissions driven by flooding in a simulation of palsa degradation

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S1 Study site

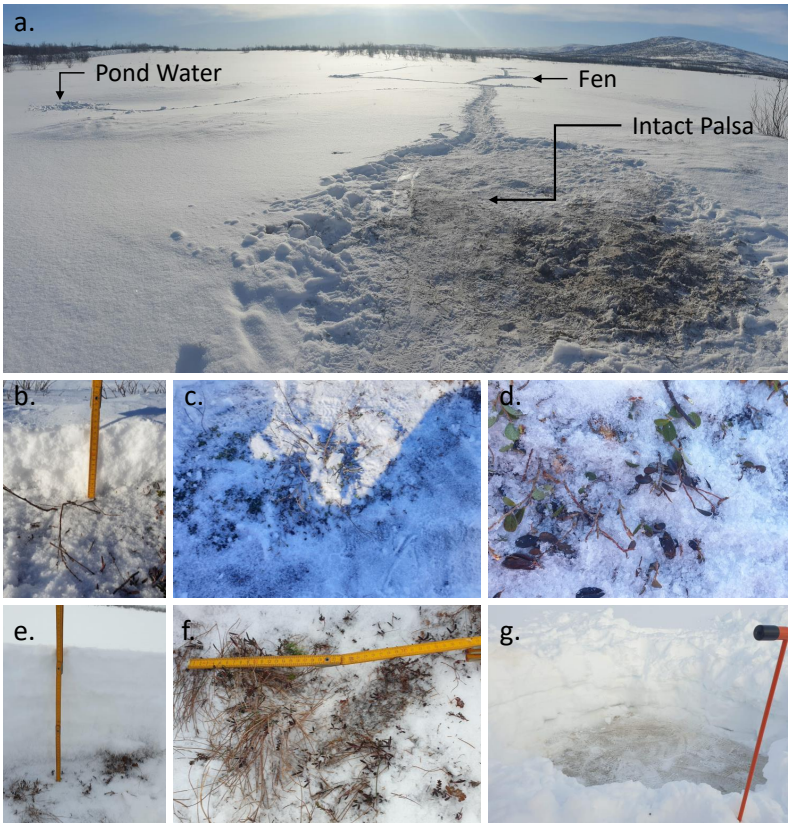

Figure S1. Sampling sites and dead vegetation still on site. Panorama of the three sampling locations: the intact palsa, the fen and the pond water (a.); Snow thickness of 16 cm at the palsa site (b.); Dominant vegetation at the palsa: dwarf shrubs (c.) and *Vaccinium ssp* (d.); Snow thickness of 46 cm at the fen site (e.); Dominant vegetation at the fen site: Sedge and Eriophorum (f.); frozen pond where the water used to inoculate part of the cores was collected (g.)

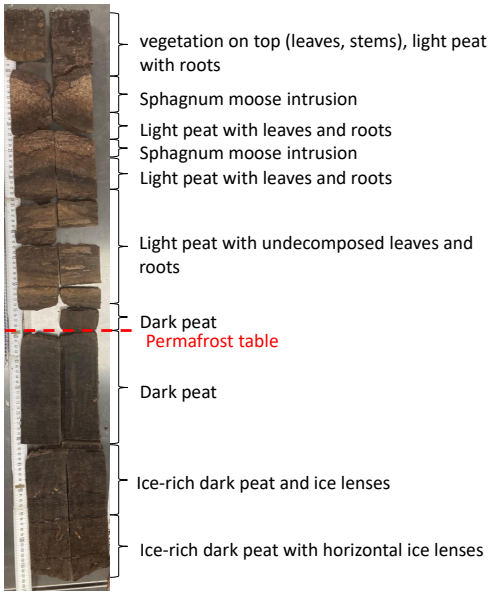

Figure S2. Core description of the palsa. The description covers the first meter and was done in the climate chamber at Alfred-Wegener-Institute. The same core was used for the geochemical analyses.

The mesocosms were incubated at the Leibniz-Zentrum für Agrarlandschaftsforschung, Müncheberg (Germany).

S2 Experimental Design

S2.0.1 Incubation chamber

The incubation chamber was made of two compartments stacked on top of each other. The bottom part was a freezer where we set the temperature at -5 °C. On top of it, we placed a styrofoam chamber, fitted to the dimension of the freezer. The styrofoam chamber was equipped with a peltier element and a ventilation system to ensure a homogeneous temperature inside the incubator. We used a resistance to set the temperature of the styrofoam chamber at 10°C. The two compartments were separated by a 6 mm styrofoam log. Holes were drilled through the separation log to insert the mesocosm tubes. To avoid air circulation between the tubes and the styrofoam log, we used foam. The tubes were held by clamps positioned inside the styrofoam chamber. We gradually thawed the mesocosms by uplifting the tubes with the clamps (Fig. S4b). We tested the incubation chamber before the incubation to ensure the temperature was stable in both compartments. During the incubation, we continuously monitored the temperature in the two compartments with HoBo Sensors (Fig. S7).

S2.0.2 Tube preparation

We incubated the cores in PVC tubes (PCV-Welt, Germany) of 1.20 m. 1 m was allocated for the cores and the remaining 0.20 m were used for the headspace (Fig. S4). Before putting the cores into the tubes, we pre-drilled the tubes where the probes would be later inserted. To avoid any contamination, we cleaned the tubes in a hydrogen peroxide bath and rinsed them with milli-Q water. Finally, we dried them in an oven.

S2.0.3 Sample preparation

The samples were transported from Kilpisjärvi to AWI Potsdam via a refrigerator truck and kept at -20 °C. Once in Potsdam, we did all the core preparation at -8 °C. For each core we scratched the outer part to remove potential contamination due to the coring. Afterward, we weighed and measured the cores before introducing them into the mesocosm tube. Then, we pushed the cores inside the tubes. Because of the coring, the cores were split into several core pieces. Therefore, we took care to match the core pieces when we inserted the cores inside the tube. We measured the headspace for each mesocosm, weighed them and remeasured the length of the core after insertion. We closed the tubes with rubber flexible pipe caps and sealed them with silicone. Finally, we pre-drilled the cores where we previously drilled the tubes. Between each core, the tools were cleaned with isopropanol. We closed the wholes with sealing tape to avoid contamination during the transport to Müncheberg. We kept the samples frozen during the transport to Müncheberg by wrapping them in aluminium foil and ice-packs.

S2.0.4 Start of the incubation

Before starting the incubation, we inserted the probes for the first 60 cm and sealed them with silicone. We fixed the samples in the incubation chamber by using clamps. We limited the air circulation between the two chambers from the holes in the styrofoam log by adding foam. We let the samples thaw overnight and then inoculated them with the different water treatments.

S2.0.5 Thawing steps

For each thawing step event the samples were manually lifted up. Following the same procedure as for the beginning of the incubation, we inserted the probes and sealed them with silicone. We inoculated the samples a day after increasing the thawed depth.

S2.0.6 Water preparation and water addition

We prepared the water treatments before each water addition.

- Autoclaved tap water: we autoclaved tap water from AWI Potsdam at ZALF, Müncheberg. The water was autoclaved to avoid microbial contamination.

– Non-filtered water: we stored the thermokarst pond water at -20°C. Before each water addition, we subsampled the water in the climate chamber using a sterilized chisel and hammer. The subsampled water was therefore put into 500mL sterile glass bottles and melted at 4°C.

– Filtered water: we used half of the melted water from the thermokarst pond for the filtered treatment. The water was filtered using a vacuum filtration system (Nalgene, Germany) with a 0.2 μm filter and stored in clean 500 mL sterile glass bottles.

We added water at four different depths: 0, 25, 50 and 75 cm. Water at 75cm was only added when the permafrost was thawed (Thaw step 0-80 cm).

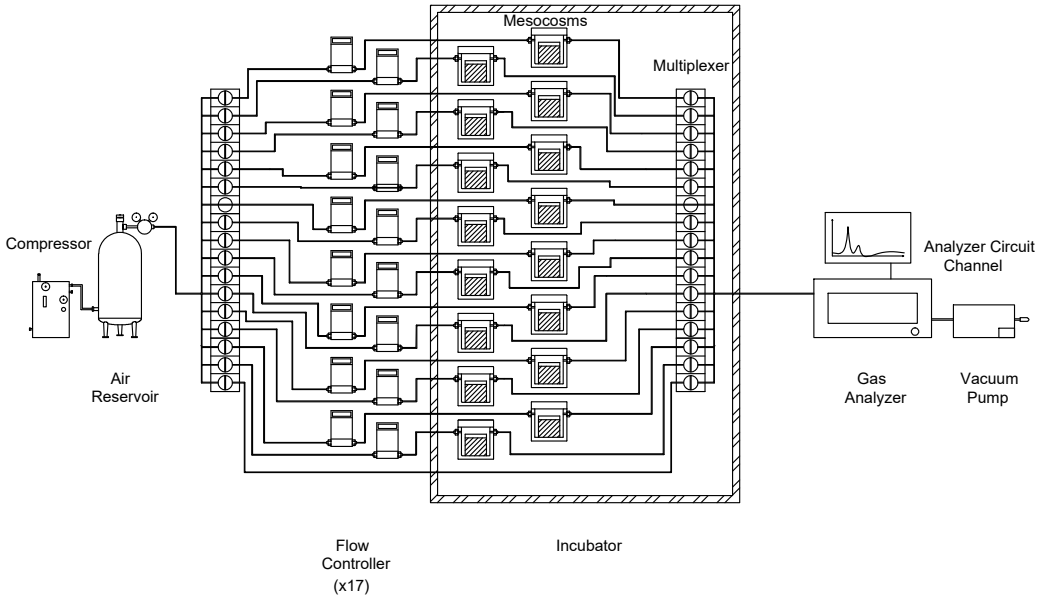

Figure S3. Schematic of the incubation setup from the Compressor to the Gas analyzer.

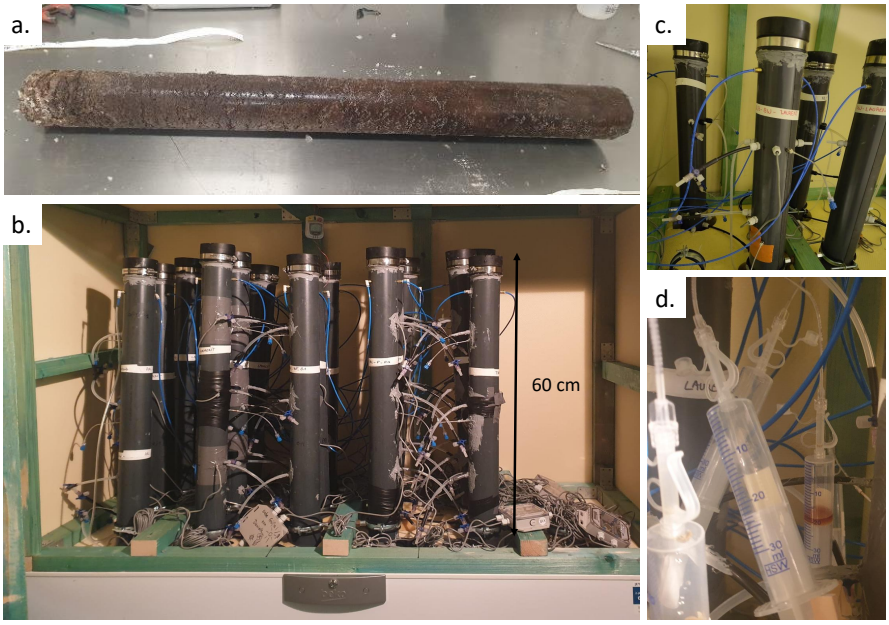

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Figure S4. Incubation setup of the mesocosms. Picture of the core from the fen after removing the oven pipe (a.); Incubation chamber with the 15 mesocosms. Here, only the first 60cm were thawed and incubated at 10°C. The bottom part represents the freezer (b.); Zoom in on the mesocosm tubes and the different probes: the 3-way valves, the rhizons and the temperature sensors. The blue cables are connected to the mesocosm headspace and to the Picarro (c.); Water sampling with syringes connected to the rhizons (d.).

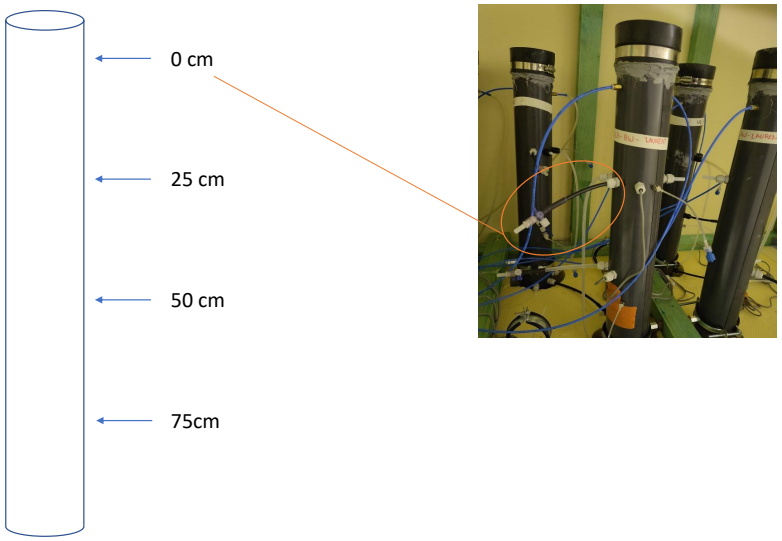

Figure S5. Depths at which the water treatments were added.

S3 Quality control prior to incubation

Prior to flux calculations we filtered out CO_2 and CH_4 measurements identified as not reliable due to the saturation of the C sensor. The Picarro Gas analyzer uses a single C sensor for CO_2 and CH_4 emissions. The high CO_2 emissions (> 5,000 ppm) from the cores were above the detection limit of the gas analyzer, leading to a saturation of the C sensor. Because of the saturation, the C sensor was likely not able to measure both CO_2 and CH_4 emissions. We identified measurements as abnormal when we measured an increase in CO_2 and a drop in CH_4 emissions simultaneously (Fig. S6). We manually reported the beginning and the end of each anomaly for every channel. Finally, we filtered out the measurements belonging to those timestamps (TableS1). The timestamps used for the quality control can be found in the data associated with the paper Laurent et al. (2023).

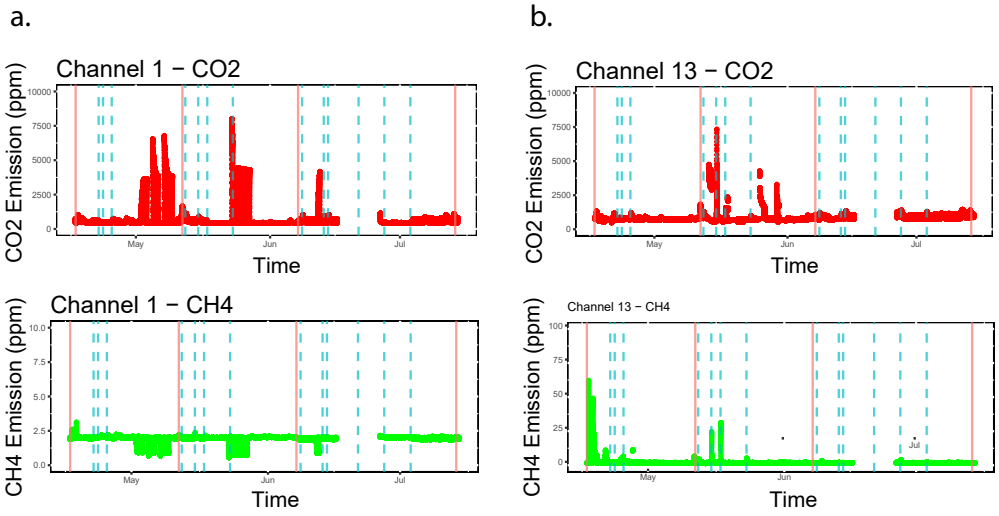

Figure S6. Comparison between abnormal measurements and measurements without the saturation effect. Example of a time series of CO_2 and CH_4 concentrations in ppm with saturation effect for specific time windows. The saturation effect is detected by inverse behavior between CO_2 and CH_4 (a.) Example of a time series of CO_2 and CH_4 emissions in ppm without saturation effect (b.)

S4 Supplementary Figures Results

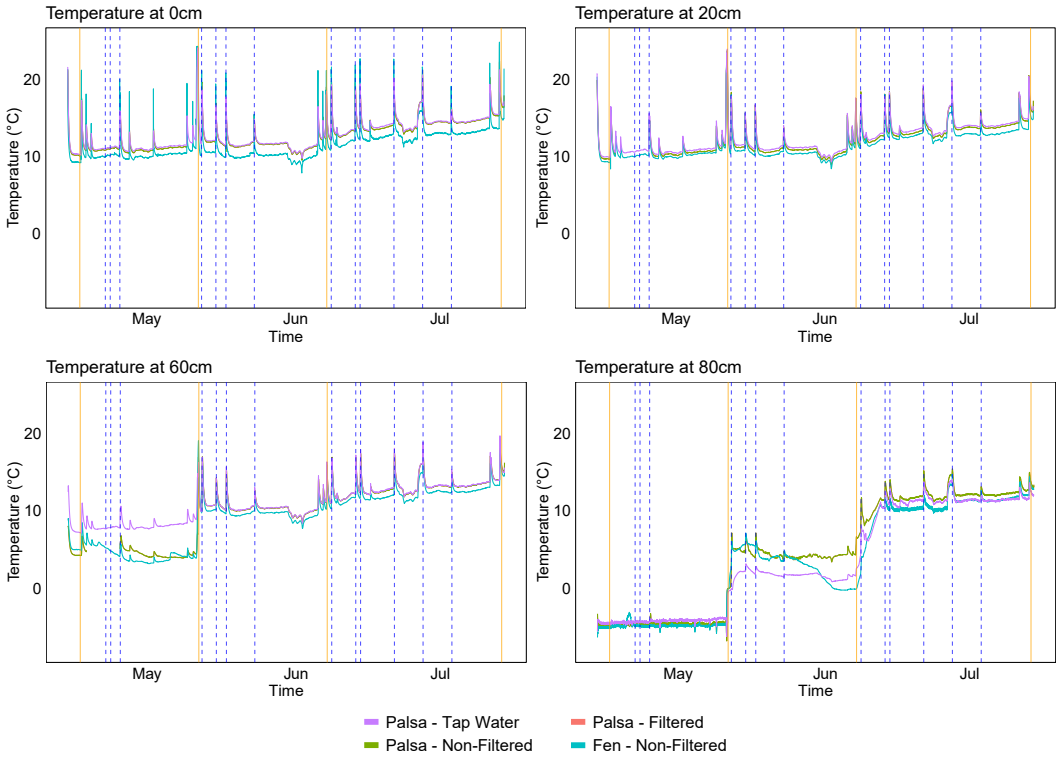

Figure S7. Monitoring of the temperature at four depths along the mesocosm tubes. Each panel shows the temperature for four out of the five treatments. The orange lines represent the thaw stage, while the blue-dashed lines indicate water addition times.

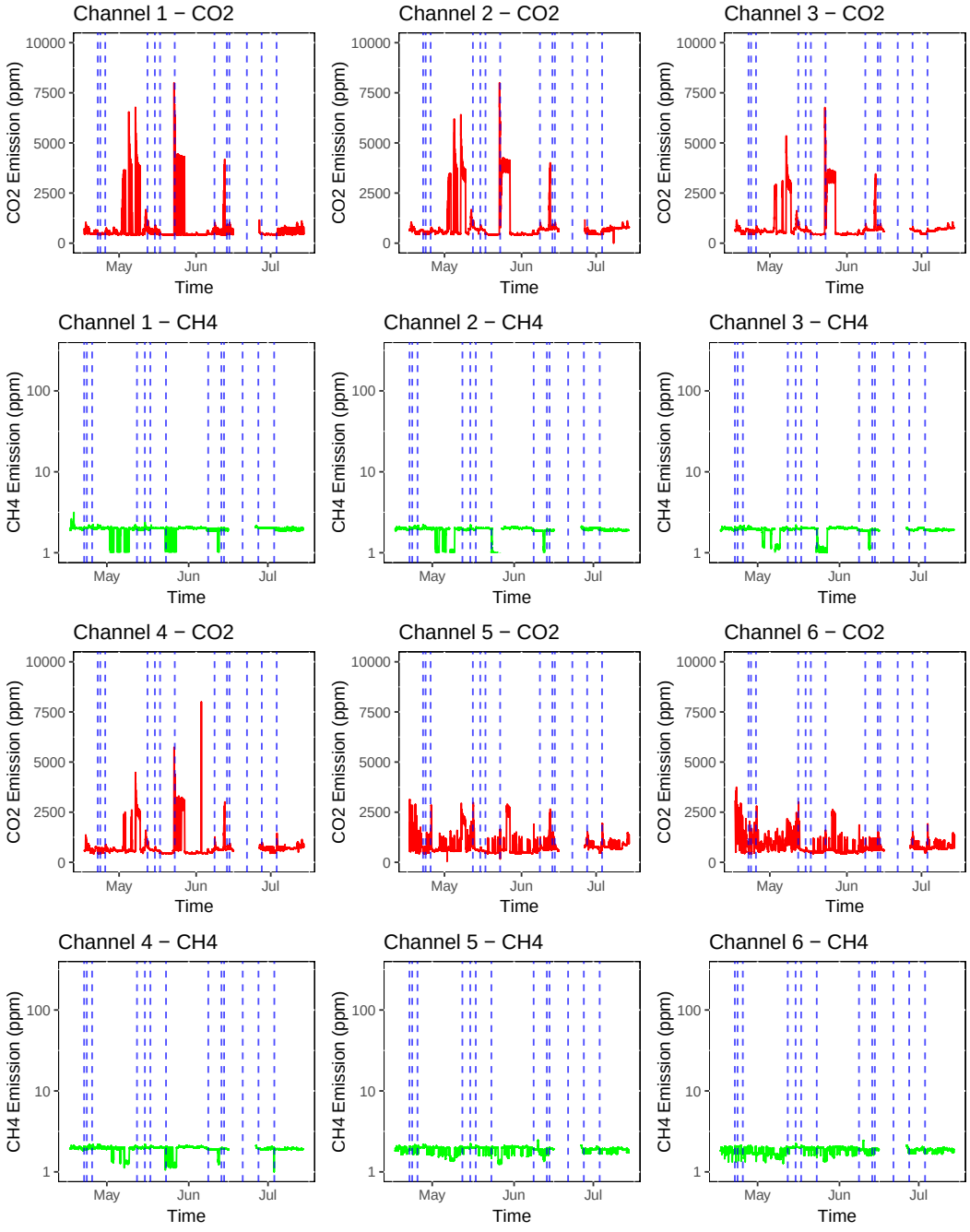

Figure S8. Raw data points of measured CO_2 and CH_4 concentrations (ppm) during the incubation. The blue-dashed lines indicate water addition times. Note that the y-axis is on a logarithmic scale. (Page 1)

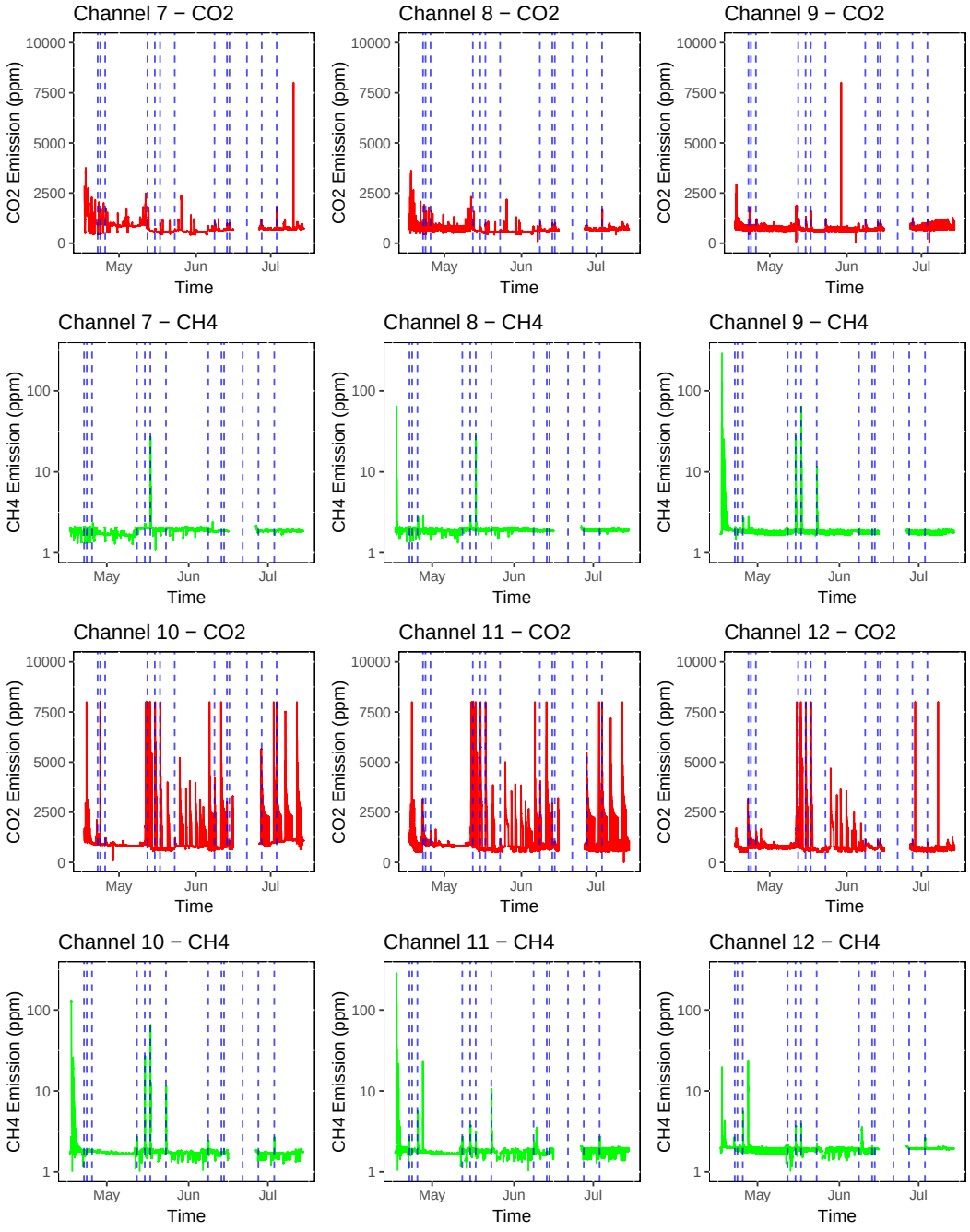

Figure S9. Raw data points of measured CO_2 and CH_4 concentrations (ppm) during the incubation. The blue-dashed lines indicate water addition times. Note that the y-axis is on a logarithmic scale. (Page 2)

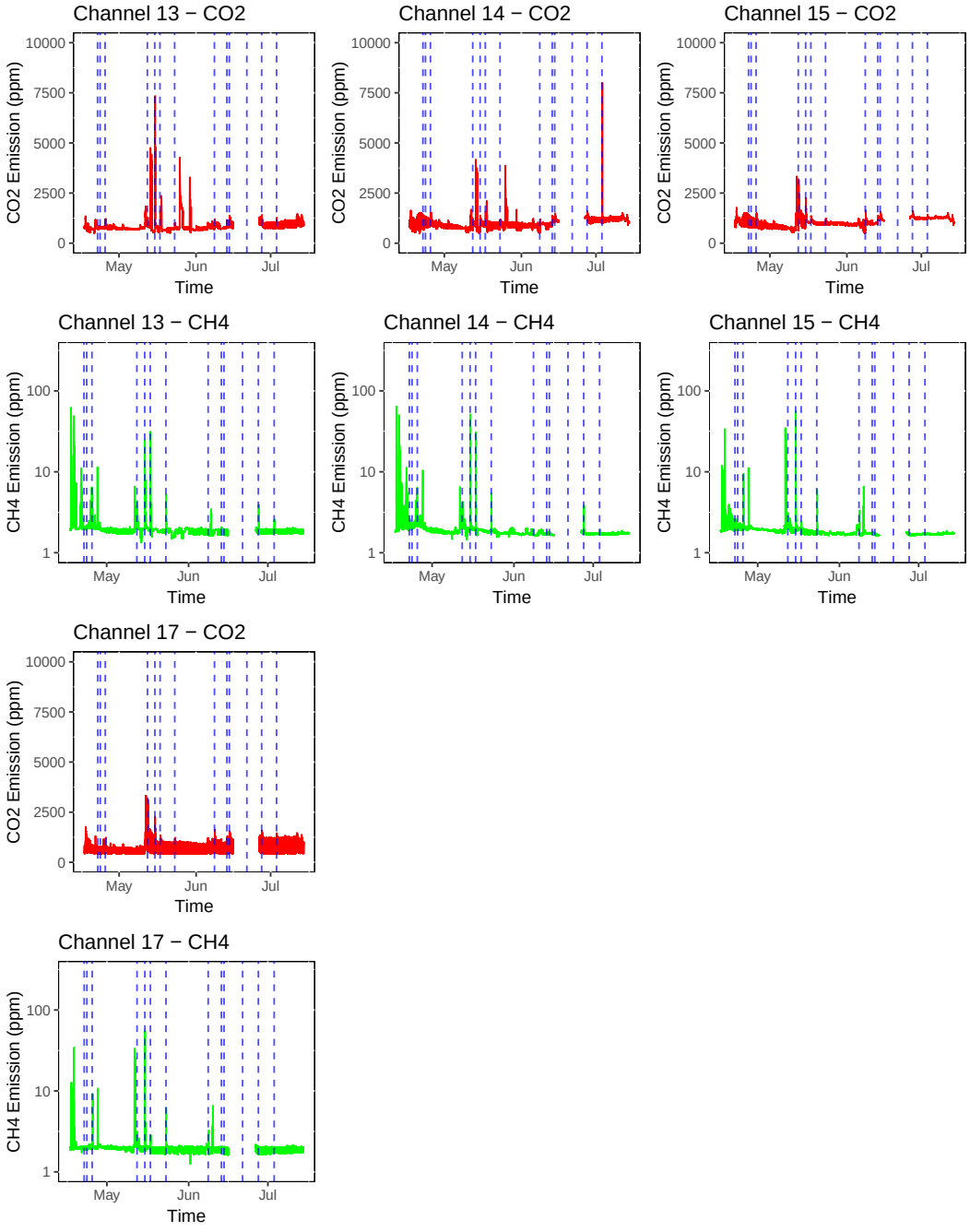

Figure S10. Raw data points of measured CO_2 and CH_4 concentrations (ppm) during the incubation. The blue-dashed lines indicate water addition times. Note that the y-axis is on a logarithmic scale. (Page 3)

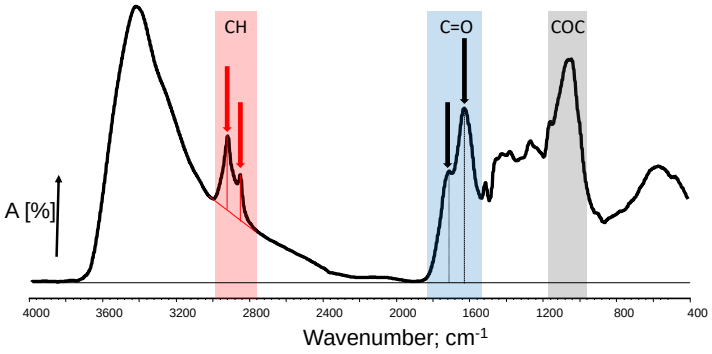

Figure S11. References for wavenumber in a FTIR spectrum. Coloured columns indicate the absorption bands of alkyl (C–H), carboxyl (C=O) and polysaccharide (COC).

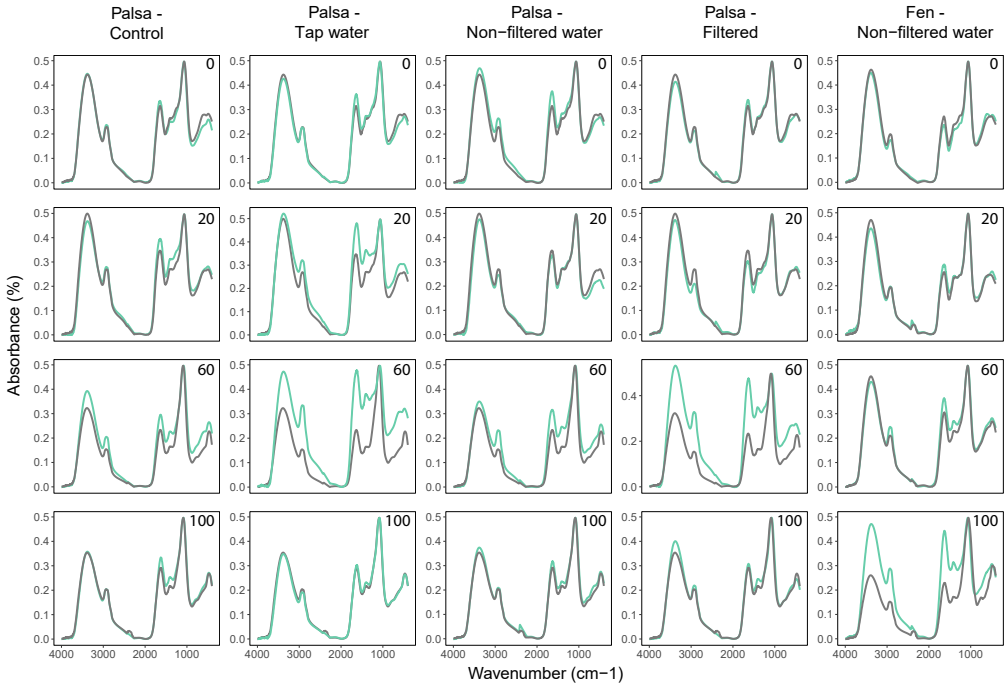

Figure S12. Peat quality along the the soil profile of the Palsa and the fen for each treatment before (grey line) and after (green line) the incubation. FTIR spectra of peat samples collected at the Palsa and fen site from 0 to 2 cm (0), 18 to 22 cm (20), 58 to 62 cm (60), and 96 to 100 cm (100).

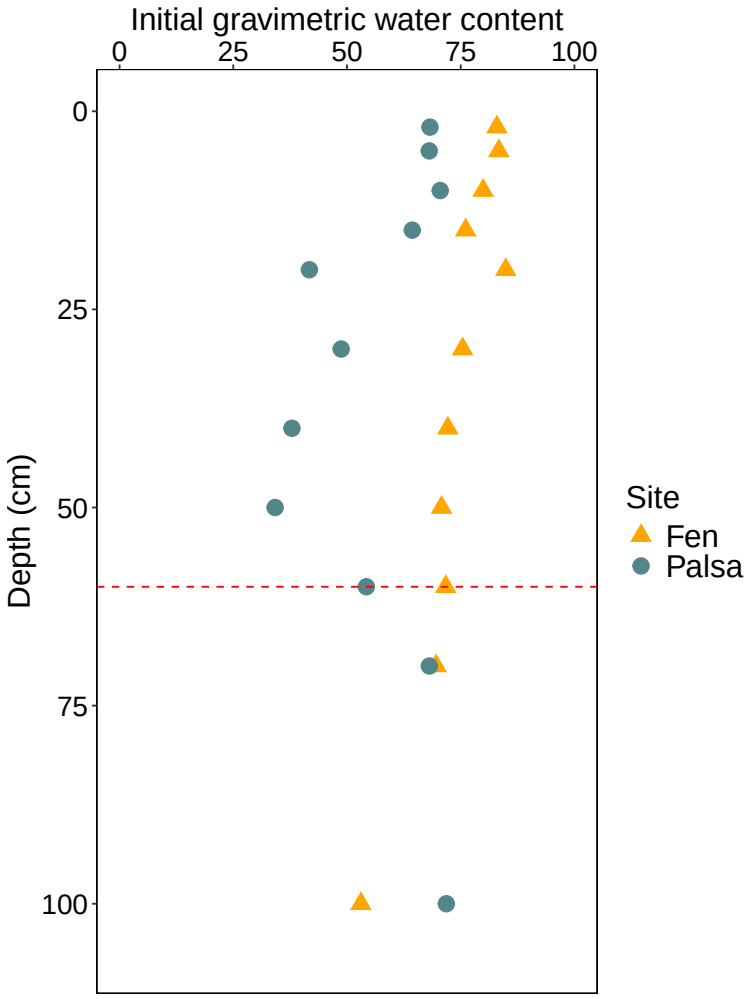

Figure S13. Initial gravimetric soil water content for the first meter of the palsa and the fen prior to incubation. The green circles indicate the values measured from the Palsa and the yellow triangle, those from the fen. The red dashed line represents the permafrost table of the Palsa.

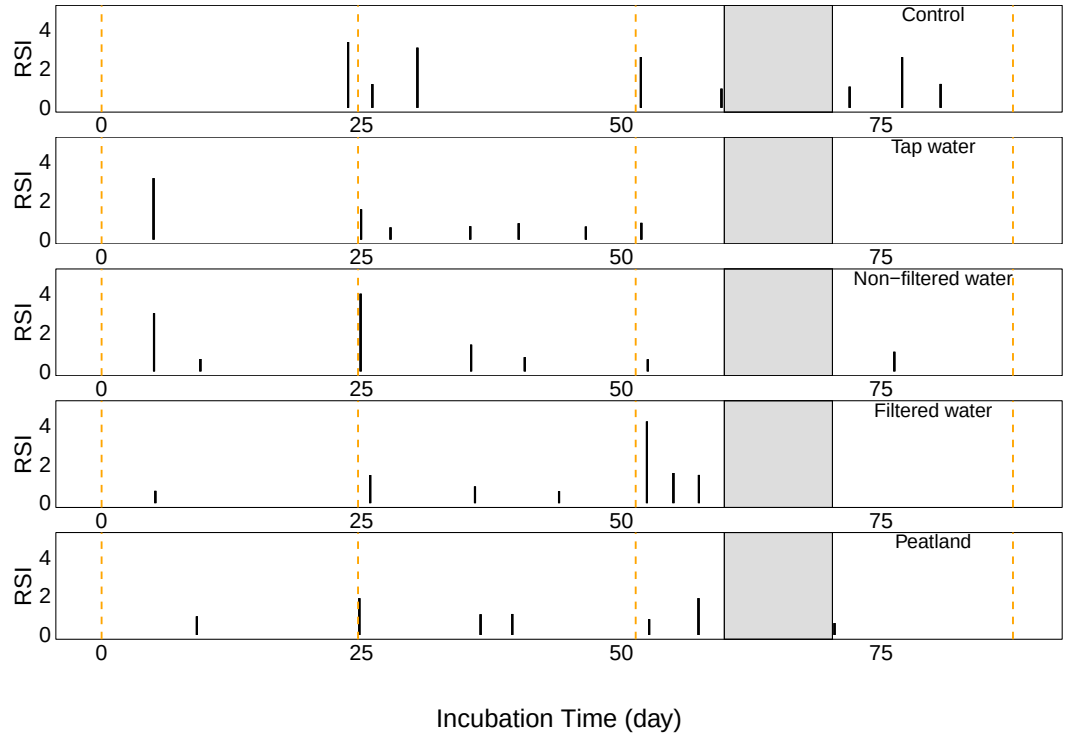

Figure S14. Detection of regime shifts in the average CO_2 emission rates for each treatment. The y-axis shows the Regime Shift Index, that indicates the strength of the regime shift event. The dashed orange lines indicate the thawing steps, while the grey area shows the time window when we had a measurement issue.

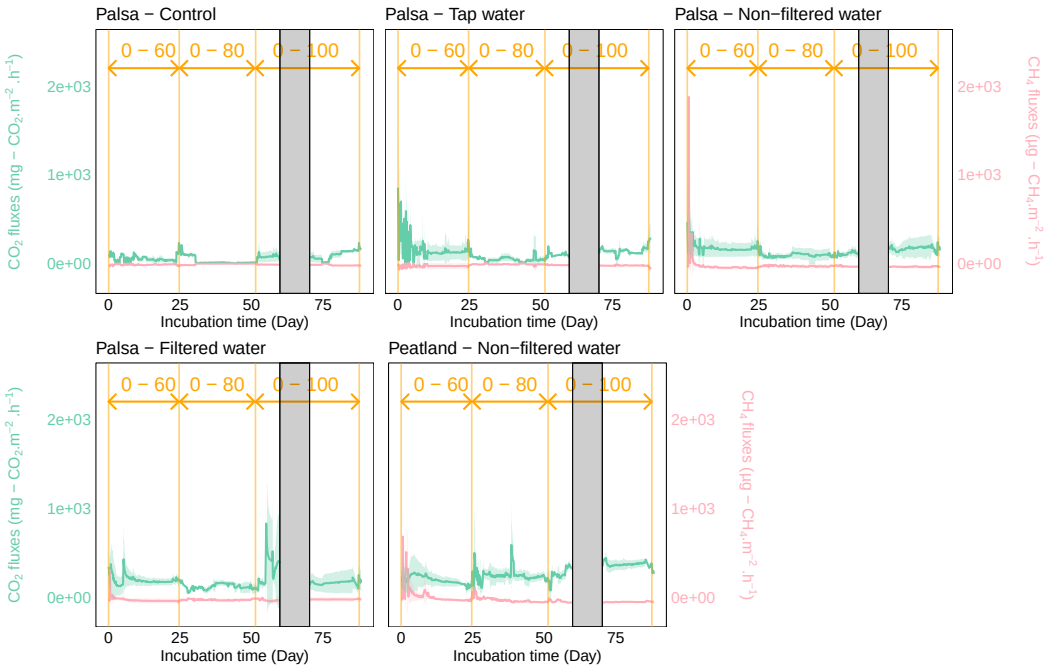

Figure S15. Average CO_2 (in green) and CH_4 (in pink) emission rates for each treatment over the course of the incubation. The orange vertical lines indicate the thawing step events. The depth of the core thawed throughout the incubation period is indicated by the numbers displayed above the arrows.

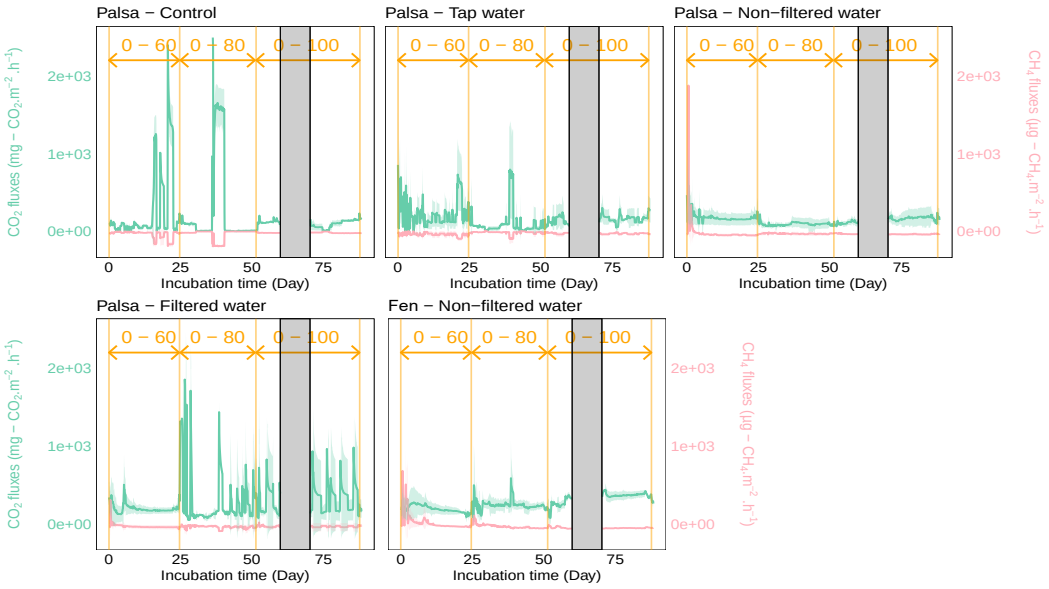

Figure S16. Average CO_2 (in green) and CH_4 (in pink) emission rates without quality control for each treatment over the course of the incubation. The orange vertical lines indicate the thawing step events. The depth of the core thawed throughout the incubation period is indicated by the numbers displayed above the arrows.

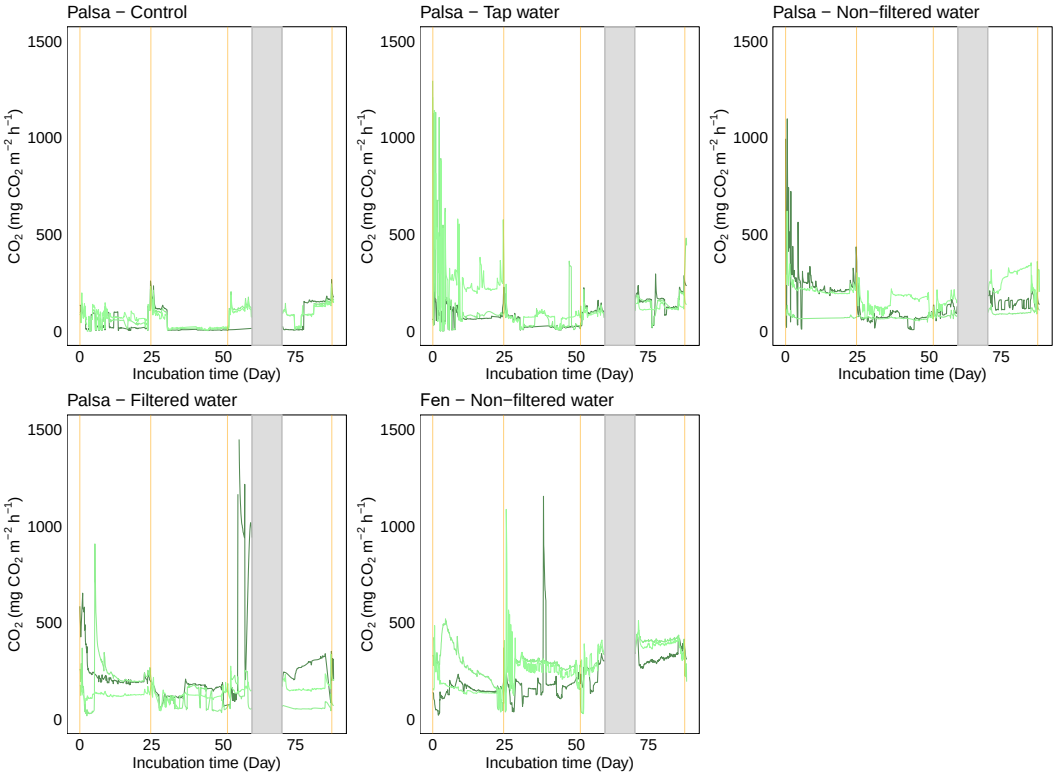

Figure S17. Continuous CO_2 emission rates for each treatment during the incubation period. The green lines in each panel represent the CO_2 emission rates for each individual replicate and the vertical orange lines indicate the thaw stages.

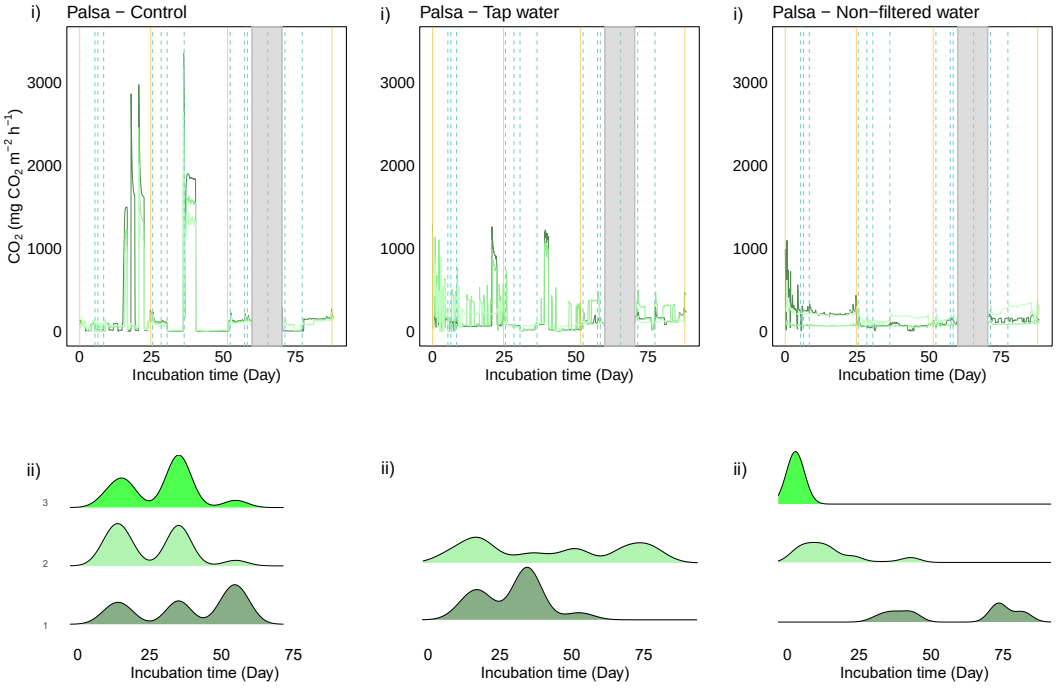

Figure S18. Panel i) shows the CO_2 flux timeseries of each replicate the vertical orange lines indicate the thaw stages and the dashed blue lines indicate the water addition times. and ii) shows the density of measured CO_2 saturation events over time. The numbers on the left refer to the channel's numbers and are identical to the ones from Table S1. Colors differentiate replicates, the vertical orange lines indicate the thaw stages and the dashed blue lines indicate the water addition times (Page 1/2)

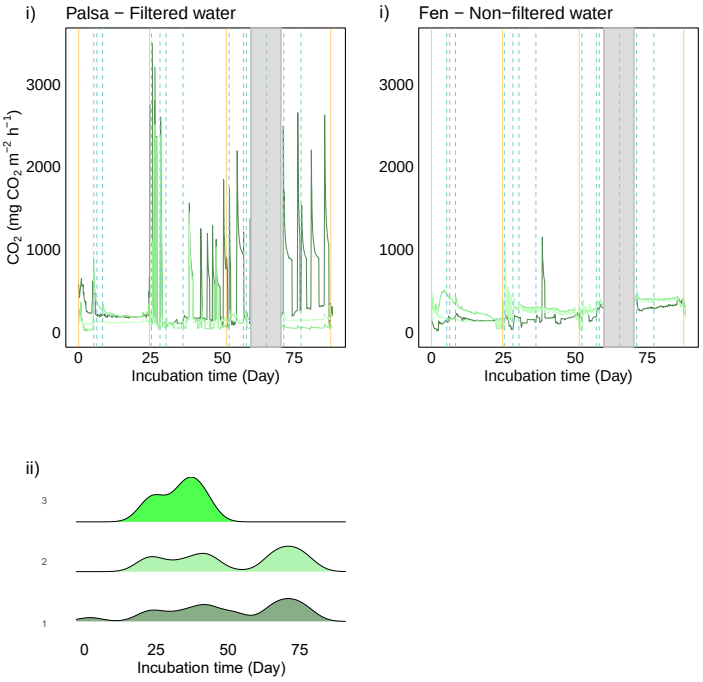

Figure S19. Panel i) shows the CO_2 flux timeseries of each replicate the vertical orange lines indicate the thaw stages and the dashed blue lines indicate the water addition times. and ii) shows the density of measured CO_2 saturation events over time. The numbers on the left refer to the channel's numbers and are identical to the ones from Table S1. Colors differentiate replicates, the vertical orange lines indicate the thaw stages and the dashed blue lines indicate the water addition times (Page 2/2)

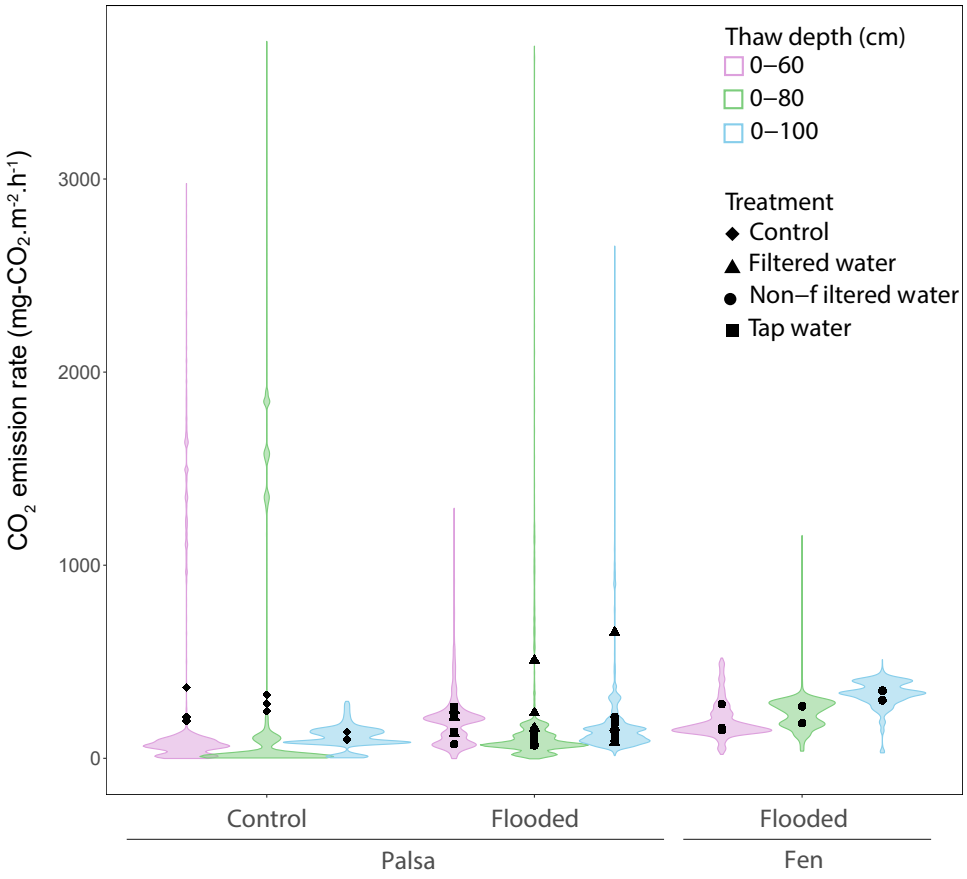

Figure S20. CO_2 emissions rates for each thaw stages under flooded or control conditions without the quality control applied. The distribution uses the time series data of CO_2 emissions from each thaw stage, under conditions (control vs. flooded) and across sites (Palsa vs. fen) to create the violin plots with the points indicating the average CO_2 emission rates for each treatment. The colors show the different thaw stage events.

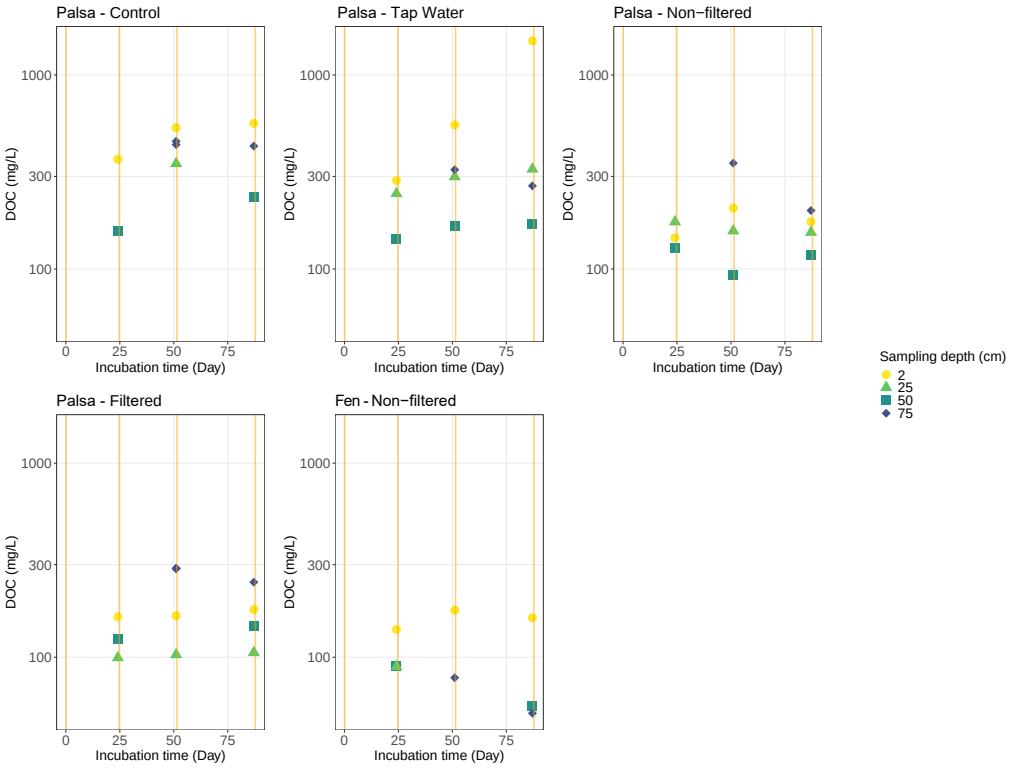

Figure S21. DOC concentrations measured in soil pore water before each thawing step. Dots represent DOC values for individual replicates, and colors indicate sampling depths. Note that for most sampling days and depths, insufficient water was collected from all replicates; often, only a single replicate yielded enough water (<5 mL) for DOC analysis.

S5 Supplementary Table Results

Table S1. Data Loss for individual channel due to the CO_2 sensor saturation during the experiment.

Site	Channel	Treatment	Total Data Points	Filtered Data Points	Data Loss (%)
Palsa	1	Control	86 000	18 326	21.54
	2	Control	86 006	10 846	12.61
	3	Control	85 949	8 352	9.72
	4	Tap water	85 910	8 159	9.50
	5	Tap water	85 855	30 117	35.08
	6	Tap water	85 850	0	0.00
	7	Unfiltered water	85 845	3 814	4.44
	8	Unfiltered water	85 840	21 569	25.13
	9	Unfiltered water	85 832	480	0.56
	10	Filtered water	85 874	27 785	32.35
	11	Filtered water	85 918	25 149	29.27
S	12	Filtered water	85 934	6 815	7.91
Fen	13	Unfiltered water	85 930	0	0.00
	14	Unfiltered water	85 839	0	0.00
	15	Unfiltered water	85 706	0	0.00
No Site	17	Zero Channel	85 960	0	0.00
Total			1 374 248	161 412	11.7

Table S2. Summary of the thawing step stages during the incubation (Depth and duration). The Permafrost thawed column only applies to the cores from the Pasla.

Week of incubation	Thaw depth (cm)	Permafrost thawed	Duration (week)
1-5	0-60	0	4
5-8	0-80	20	4
9-12	0-100	40	4

Table S3. pH and conductivity values of the thermokarst water used for the Non-filtered and Filtered treatments.

Sample	pH	Conductivity (μS.cm^{-1})	DOC (mg.L^{-1})
Thermokarst water	4.2	300	9.68

Table S4. Comparison of statistical tests (Kruskal–Wallis test followed by pairwise comparisons using Dunn's test) results before and after QC (quality control) (adjusted p-values). "sig." indicates significant after multiple testing correction (p = 0.05) and "n.s" indicates non-significant. Note that the numbers in the comparison list indicate the depth in cm.

Comparison	After QC	Before QC	Outcome
Control_100_Palsa – Control_60_Palsa	n.s.	n.s.	consistent
Control_100_Palsa – Control_80_Palsa	n.s.	n.s.	consistent
Control_60_Palsa – Control_80_Palsa	n.s.	n.s.	consistent
Control_100_Palsa – Flooded_100_Palsa	n.s.	n.s.	consistent
Control_60_Palsa – Flooded_100_Palsa	n.s.	n.s.	consistent
Control_80_Palsa – Flooded_100_Palsa	n.s.	n.s.	consistent
Control_100_Palsa – Flooded_100_Peatland	n.s.	n.s.	consistent
Control_60_Palsa – Flooded_100_Peatland	sig.	sig.	consistent
Control_80_Palsa – Flooded_100_Peatland	sig.	sig.	consistent
Flooded_100_Palsa – Flooded_100_Peatland	n.s.	n.s.	consistent
Control_100_Palsa – Flooded_60_Palsa	n.s.	n.s.	consistent
Control_60_Palsa – Flooded_60_Palsa	sig.	sig.	consistent
Control_80_Palsa – Flooded_60_Palsa	sig.	sig.	consistent
Flooded_100_Palsa – Flooded_60_Palsa	n.s.	n.s.	consistent
Flooded_100_Peatland – Flooded_60_Palsa	n.s.	n.s.	consistent
Control_100_Palsa – Flooded_60_Peatland	n.s.	n.s.	consistent
Control_60_Palsa – Flooded_60_Peatland	n.s.	n.s.	consistent
Control_80_Palsa – Flooded_60_Peatland	n.s.	n.s.	consistent
Flooded_100_Palsa – Flooded_60_Peatland	n.s.	n.s.	consistent
Flooded_100_Peatland – Flooded_60_Peatland	n.s.	n.s.	consistent
Flooded_60_Palsa – Flooded_60_Peatland	n.s.	n.s.	consistent
Control_100_Palsa – Flooded_80_Palsa	n.s.	n.s.	consistent
Control_60_Palsa – Flooded_80_Palsa	n.s.	n.s.	consistent
Control_80_Palsa – Flooded_80_Palsa	n.s.	n.s.	consistent
Flooded_100_Palsa – Flooded_80_Palsa	n.s.	n.s.	consistent
Flooded_100_Peatland – Flooded_80_Palsa	sig.	sig.	consistent
Flooded_60_Palsa – Flooded_80_Palsa	sig.	sig.	consistent
Flooded_60_Peatland – Flooded_80_Palsa	n.s.	n.s.	consistent
Control_100_Palsa – Flooded_80_Peatland	n.s.	n.s.	consistent
Control_60_Palsa – Flooded_80_Peatland	sig.	sig.	consistent
Control_80_Palsa – Flooded_80_Peatland	sig.	sig.	consistent
Flooded_100_Palsa – Flooded_80_Peatland	n.s.	n.s.	consistent
Flooded_100_Peatland – Flooded_80_Peatland	n.s.	n.s.	consistent
Flooded_60_Palsa – Flooded_80_Peatland	n.s.	n.s.	consistent
Flooded_60_Peatland – Flooded_80_Peatland	n.s.	n.s.	consistent
Flooded_80_Palsa – Flooded_80_Peatland	sig.	sig.	consistent

References

Laurent, M., Lück, M., and Treat, C. C.: Continuous CO_2, CH_4 and H_2O fluxes measured during a 3-month mesocosm incubation from a Palsa, https://doi.org/10.1594/PANGAEA.974302, dataset, 2023.