Slicing a peat pie: just 5 cm of topsoil removal strongly reduces CH_4 emission after rewetting

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Abstract

Topsoil removal (TSR) is a management action performed before rewetting drained agricultural peatlands to reduce greenhouse gas (GHG) emissions and nutrient leaching. The current common practice to remove 30 to 60 cm of topsoil is labor-intensive, costly, and highly invasive. However, the optimal TSR depth for mitigating carbon emissions from rewetted peat soils has neither been determined nor linked to soil biogeochemical factors driving carbon emissions.

We executed two mesocosm experiments to address this. In experiment 1, we removed the topsoil of two contrasting peat soils before rewetting (i.e., extensively managed, acid peat *and* intensively managed, near-neutral peat) with increments of 5 cm up to 25 cm TSR. In experiment 2, we combined TSR with the presence and absence of *Typha latifolia* on intensively managed, near-neutral peat soil. The experiments ran for 22 and three months, respectively, in which we measured carbon dioxide (CO_2) and methane (CH_4) emissions and porewater chemistry.

Our experiments show that i) 5 cm TSR greatly reduced CH_4 and CO_2 emissions irrespective of peat nutrient status during the 22-month experiment, and ii) the presence of *T. latifolia* further reduced CH_4 emissions during the 3-month experiment. Specifically, CH_4 emissions were six to 10-times lower with 5 cm TSR compared to 0 cm TSR. Peak CH_4 emissions occurred after three months with 0 cm TSR and strongly decreased thereafter. Random forest analyses showed that variation in CH_4 emissions could mainly be explained by cumulative root biomass and porewater alkalinity. Furthermore, 5 cm TSR reduced porewater values of pH, alkalinity, CH_4, and ammonium. The effectiveness of TSR in preventing the build-up of phosphorus, iron, and sulfur in porewater was site-specific.

This experimental study highlights that only 5 to 10 cm TSR may already effectively prevent adverse effects of peatland rewetting by cutting undesirable CH_4 emissions and avoiding nutrient release. This study clarifies that target settings and site-specific assessments are crucial to decide on the amount of TSR for peatland restoration and paludiculture.

Keywords: greenhouse gas emissions, peatland restoration, climate mitigation, root biomass, TSR, *Typha*

1 Introduction

Although peatlands cover only 3% of the global land area, they store 30% of global soil carbon (Yu 2012; Leifeld and Menichetti 2018; Chaudhary et al. 2020). Historical drainage for agriculture has turned large areas of peatlands into carbon sources, accounting for 5% of the global anthropogenic CO_2 emissions (Cobb et al. 2017; Chaudhary et al. 2020; IPCC 2021). To mitigate carbon emissions from peatlands and restore their function as carbon sinks worldwide, peatland rewetting is proposed as an important measure (IPCC 2021; Evans et al. 2021; Temmink et al. 2022). While increasing water levels in drained peatlands can reduce CO_2 emissions, they are known to stimulate CH_4 emissions (Evans et al. 2021). In the long-term, however, rewetting degraded peat benefits the climate despite CH_4 emissions (Günther et al. 2020).

In natural peat soils, a high-water table leads to anoxic conditions due to continued oxygen (O_2) consumption and near-absent O_2 intrusion (Laanbroek 1990; Rydin and Jeglum 2013; Conrad 2020). Rewetting of peat soils results in rapid depletion of O_2 availability and initiates the reduction of alternative electron acceptors, preferentially in the sequence of nitrate, manganese, ferric iron, and sulfate before CH_4 production starts (Glaser and Chanton 2009; Rydin and Jeglum 2013; Conrad 2020). CH_4 production is mainly substrate-limited (Segers 1998; Drake et al. 2009), and in peatlands, pathways of CH_4 production are primarily the reduction of acetate (more than 70%) and CO_2 (Smolders et al. 2002; Artz 2009). Therefore, CH_4 production is suppressed as long as concentrations of methanogenic substrates (e.g., H_2, acetate) are limited by the presence of alternative electron acceptors (Conrad 2020). The availability of alternative electron acceptors and the time required for the growth of methanogenic archaea and other anaerobic microorganisms result in a lag phase of CH_4 production (Hahn-Schöfl et al. 2011; Conrad 2020). Rewetting may thus shift drainage-based CO_2-emission to CH_4-dominated emissions (Wilson et al. 2016a; Renou-Wilson et al. 2019; McNicol et al. 2020).

Topsoil removal (TSR) has recently been shown as an effective measure to reduce GHG emissions after peatland rewetting on a field scale (Harpenslager et al. 2015; Huth et al. 2020). The main mechanism of this reduction by soil preparation is the removal of the peat layer with the highest labile carbon content, including shoots, roots, and humic soil (Harpenslager et al. 2015; Huth et al. 2020). The standard practice of TSR is to remove about 30 to 60 cm of peat (Allison and Ausden 2004; Gaudig et al. 2018; Huth et al. 2020). This depth is often used to remove labile carbon and the nutrient-rich topsoil layer, which is especially important for paludiculture practices (i.e., the cultivation of crops on wet or rewetted agricultural peatlands). Since rewetted peatlands are often former agricultural sites, the maintained productivity of a site is often preferred, as it is a win-win situation for the climate and the landowner (Budiman et al. 2020). For instance, in *Sphagnum* paludiculture, TSR minimizes the competition between mosses and fast-growing plants (Gaudig et al. 2017), but also removes the highly decomposed layer with low porosity and hydraulic conductivity that hampers *Sphagnum* growth (Gaudig et al. 2018; Grobe et al. 2021). Besides causing a substantial change in the environment, TSR is a costly practice and may thus put a large constraint on the willingness to restore peatland functioning by rewetting (Klimkowska et al. 2010; Zak et al. 2018; Convention on Wetlands 2021).

Interestingly, the mechanisms driving the contribution of individual soil layers and vegetation of rewetted peat to GHG emissions are poorly understood. For instance, the factors ruling hotspot formation of CH_4 production, including electron acceptor availability and shunt effects of tall growing plant species, are not fully known (Fenner et al. 2011). Although CH_4 production is expected to occur after the depletion of alternative electron acceptors (Smolders et al. 2002; Hahn-Schöfl et al. 2011; De Jong et al. 2020), researchers also found contrasting results (Knorr and Blodau 2009). Similarly, the presence of vascular plants can affect CH_4 emissions positively or negatively by increasing CH_4 oxidation or favoring CH_4 transportation to the atmosphere by the roots (Fritz et al. 2011; Agethen et al. 2018; Huth et al. 2020).

To bring more clarity, we performed two mesocosm experiments, removing topsoil with 5-cm increments up to 25 cm before rewetting on nutrient-wise contrasting peat soils, and with and without the growth of *Typha latifolia*, a common paludiculture species. We determined GHG fluxes and porewater chemistry during 22 and three months for the first and second experiments, respectively. With this study, we aimed to answer the following research questions:

1. What is the mitigation potential of minimal TSR (i.e., compared to the standard practice) and the presence of *T. latifolia* on the GHG emission of rewetted peat soils?

2. How is the nutrient availability of rewetted peat soils affected by minimal TSR and the presence of *T. latifolia*?

3. What are the main drivers of CH_4 emissions from rewetted peat soils?

Our hypotheses are: (1) we expect higher CH_4 emission in the 0 cm TSR treatment due to the higher availability of labile carbon and nutrients. In addition, we expect higher CH_4 emissions in the presence of *T. latifolia* due to the increased transportation of CH_4 from the soil to the atmosphere (shunt effect). (2) We expect reduced nutrient concentrations with TSR due to direct nutrient removal. In addition, we expect lower nutrient concentrations with the presence of *T. latifolia* due to plant uptake. (3) We expect the labile carbon to be the biggest driver of CH_4 emissions from rewetted peat soils by limiting or supporting methanogenesis.

2 Materials and methods

2.1 Sampling

At two sites in the Netherlands, peat soil cores with a depth of 30 cm were taken using 15 cm diameter PVC-pipes at two sites (Vroom et al. 2022). The first site is an extensively managed agricultural peat meadow in Bûtefjild (coordinates: 53°15'N, 5°57'E), which has acid peat (pH 4.4), and it will be referred to as EA (i.e., extensively managed and acid peat). The second site is a drained, intensively managed agricultural peat meadow in Zegveld (coordinates: 52°08'N, 4°50'E), which has near-neutral peat (pH 5.6), and it will be referred to as IN (i.e., intensively managed and near-neutral peat). We collected these contrasting sites to assess the site and history dependency on GHG fluxes and nutrient removal (i.e., different agricultural history, nutrient availability, and pH). These cores were used for two separate experiments. For experiment 1, both peat types were investigated, while for experiment 2, only IN was used.

2.2 Experiment 1: topsoil removal every 5 cm

In the first experiment, we investigated the effects of TSR on GHG emissions and nutrient availability by removing the topsoil of the collected peat cores at 5 cm intervals, incrementally, up to 25 cm (Fig. 1A). In the 0 cm TSR, only the aboveground grass biomass was removed, leaving 5 cm long stubbles. The experiment was performed using four replicates distributed randomly in a dark climate chamber of the Radboud University in the Netherlands with an air temperature of 15 °C and relative humidity of 70%. The peat cores were placed in slightly larger cylinders and inundated with 5 cm of demineralized water. The water level was kept constant throughout the experiment by the regular addition of demineralized water. The experiment ran for 22 months, from March 2016 until December 2017.

2.3 Experiment 2: interaction between topsoil removal and presence of T. latifolia

In the second experiment, we investigated the effects of TSR coupled with the presence of *T. latifolia*, a typical paludiculture and wetland species, on CH_4 emissions and nutrient availability. Only IN soil was used, with three TSR depths (0, 5, and 15 cm) in the presence and absence of *T. latifolia* (Fig. 1B). In contrast to experiment 1, in the 0 cm TSR the aboveground grass biomass was not trimmed back. The cores were placed in a temperature-controlled water bath at 14 °C in the Radboud University greenhouse facilities after they were closed at the bottom with a PVC cap and were placed in a plastic bag (open at the top). Each core was inundated up to the peat surface using rainwater. For each TSR treatment, five cores were planted with three *T. latifolia* seedlings (± 5 cm each) (on day 0; total $n = 15$). Seedlings were raised in the greenhouse from seeds collected at Deurnese Peel in the Netherlands (coordinates: 5°52’29’’E; 51°25’20’’N). Three cores per TSR treatment were not vegetated and served as controls (total $n = 9$). The unvegetated cores were covered by dark perforated plastics to avoid algae growth. For brevity, the treatments with *T. latifolia* are called ‘*Typha’* and unvegetated controls ‘unvegetated’ hereafter. Twelve days after planting the seedlings, the water table in all cores was raised to 5 cm above the peat surface and kept steady throughout the experiment by the regular addition of rainwater. The experiment ran for three months, from April to June 2018.

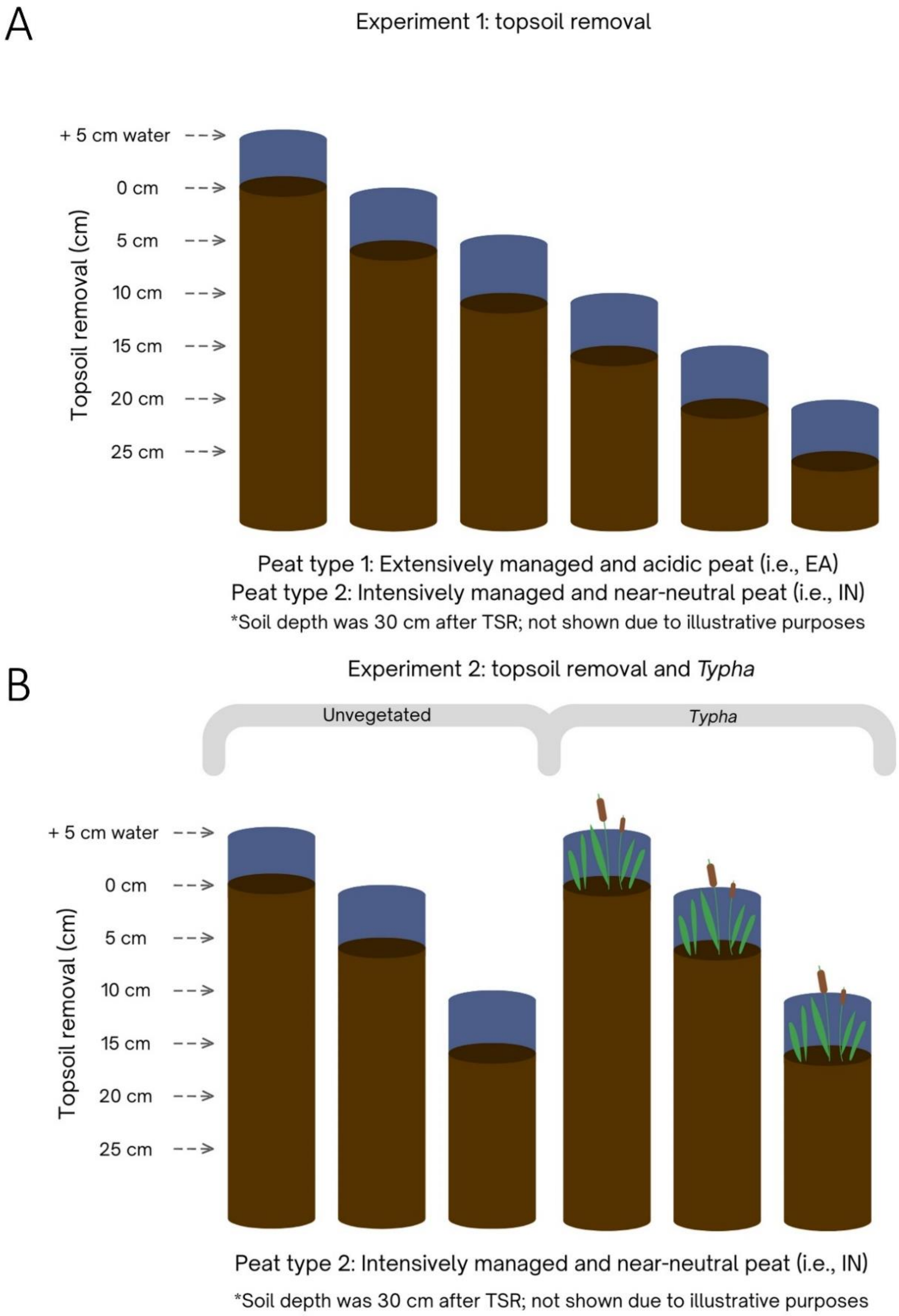

Fig. 1 Overview of the experimental setup of experiments 1 (A) and 2 (B). Soil depth was 30 cm after topsoil removal (TSR); not shown due to illustrative purposes.

2.4 Measurements

Methane (CH_4) and carbon dioxide (CO_2) fluxes were measured six times during experiment 1 (months 1, 2, 3, 10, 19, and 22) and three times during experiment 2 (months 1, 2, and 3). Gas measurements were carried out using a dark PVC chamber (15 cm inner diameter), which was connected to a Los Gatos Greenhouse Gas Analyzer (GGA-24EP, Los Gatos Research, Mountain View, CA, USA) for experiment 1 and to an Ultraportable Greenhouse Gas Analyzer (UGGA-30EP, Los Gatos Research, Mountain View, CA, USA) for experiment 2. A battery-driven fan allowed constant airflow in the chamber. The measurements lasted for 180 seconds and were repeated if ebullition was observed (i.e., in case of an abrupt increase in gas concentration). Simultaneously to the gas measurements, the air temperature was logged using a HOBO logger (Onset Computer Corporation, Bourne, MA, USA). CH_4 and CO_2 fluxes (mg m^{-2} d^{-1}) were calculated following Almeida et al. (2016):

$$F = \frac{V}{A} * slope * \frac{P * F1 * F2}{R * T}$$

Where F is CH_4 or CO_2 flux (mg m^{-2} d^{-1}); V is chamber volume (m^3); A is chamber surface area (m^2); slope is the slope of the relationship between CH_4 or CO_2 and time (ppm s^{-1}); P is atmospheric pressure (kPa); F1 is the molecular weight (CO_2: 44 and CH_4: 16 g $mole^{-1}$); F2 is the conversion factor of seconds to days; R is the gas constant (8.3144 J K^{-1} $mole^{-1}$); and T is the temperature in Kelvin (K).

CH_4 in the porewater from the upper 10 cm of peat was sampled twice during experiment 1 (months 2 and 3), and three times during experiment 2 (months 1, 2, and 3). The porewater CH_4 was collected using rhizon samplers (Rhizosphere Research Products, Wageningen, The Netherlands) attached with a needle to a pre-vacuumed 12 mL exetainer (Labco, Lampeter, UK) containing 1 mL of hydrochloric acid (0.1 M) to stop the biological activity. The samples were, then, analysed by equilibrating with the headspace of ambient air immediately after sampling and measuring the gas phase on an HP 5890 gas chromatograph equipped with a Porapak Q column (80/100 mesh) and a flame ionization detector (GC-FID, Hewlett Packard, Palo Alto, CA, USA). Concentrations were calculated using Henry's law (Sander 2015).

Porewater chemical composition from the upper 10 cm of peat was determined from samples taken four times during experiment 1 (months 1, 2, 3, and 10) and three times during experiment 2 (months 1, 2, and 3) using the same rhizon samplers attached to a syringe under vacuum. The samples were analysed following the approach described by Vroom et al. (2022) to determine pH, alkalinity, ammonium (NH_4^+), phosphorus (P), iron (Fe), and sulfur (S). The pH and alkalinity were determined using Ag/AgCl electrode (Orion Research, Beverly, MA, USA) and a TIM 840 Titration Manager (Radiometer Analytical SAS, Villeurbanne, France). NH_4^+ was determined by colorimetric methods (Auto Analyser III, Bran and Luebbe GmbH, Norderstedt, Germany). P, Fe, and S were determined using an inductively coupled plasma emission spectrometry (ICP-OES, IRIS Intrepid II, Thermo Electron Corporation, Franklin, MA, USA).

For experiment 1, root samples were washed from additional cores that were not rewetted ($n = 4$). The 15 cm diameter cores were sliced every 5 cm to a depth of 30 cm. The samples were thoroughly rinsed to retain the roots (living and dead), after which the material was weighed, dried at 70 °C for 96 hours, and weighed again.

2.5 Statistical analyses

GHG emissions were log-transformed before all analyses. To enable the inclusion of extremely low CH_4 fluxes (± 1 mg m^{-2} day^{-1}), these were set to 0 after the transformation. We did not filter fluxes based on their fit (R^2). Negative fluxes (< -1 mg m^{-2} day^{-1}; $n = 7$ for CH_4 from experiment 1, $n = 0$ for CH_4 from experiment 2, and $n = 15$ for CO_2 from experiment 2) were removed from all analyses, since this study focused on emissions only.

The effect of TSR depths and the effect of *Typha* on GHG emissions (RQ1) of rewetted peat soils were assessed using three-way repeated-measures ANOVAs. For experiment 1, differences in CH_4 emission and CO_2 emission were separately assessed using TSR treatment, peat type (EA *vs.* IN), time (the month into the experiment), and their interactions as independent variables. For experiment 2, differences in CH_4 emission were assessed using TSR treatment, plant presence, time (the month into the experiment), and their interactions as independent variables, after extreme outliers' removal ($n = 1$). Since the response variables were not normally distributed according to the Shapiro-Wilk normality test, differences between individual treatments that proved significant in the ANOVA were tested using the non-parametric Wilcox paired samples post-hoc tests with Bonferroni correction of *p* values.

The effect of TSR depths and the effect of *Typha* growth on nutrient availability (RQ2) of rewetted peat soils were assessed using three-way repeated-measures ANOVAs. For experiment 1, differences in the grass and root biomass, porewater CH_4 concentrations, and porewater nutrient concentrations were separately assessed using TSR treatment, peat type (EA *vs.* IN), time (the month into the experiment), and their interactions as independent variables. For experiment 2, differences in porewater CH_4 concentrations and nutrient concentrations were assessed using TSR treatment, plant presence, time (the month into the experiment), and their interactions as independent variables. To test for differences between individual treatments that proved significant in the ANOVA, we used pairwise t-tests for porewater alkalinity, pH, P, and Fe and the non-parametric Wilcox paired samples test for porewater CH_4, NH_4^+, and S because these variables were not normally distributed. All post-hoc tests were performed with Bonferroni correction of *p* values.

We performed two random forest analyses for both experiments to determine the main drivers of the mitigation potential for CH_4 emissions (RQ3). For experiment 1, measurements over months 1, 3, and 10 were used as they had complete measurements. The CH_4 fluxes were the dependent variable, and CO_2 flux, cumulative CO_2, cumulative root biomass, time (the month into the experiment), soil type, and porewater results (alkalinity, pH, NH_4^+, Fe, S, and P) were used as independent variables. For experiment 2, CH_4 emissions were also used as the dependent variable, and time (the month into the experiment), vegetation treatment, and porewater results (alkalinity, pH, NH_4^+, Fe, S, and P) as independent variables. Porewater CH_4 concentration was not included in the random forest, because it was not measured during the whole experiment 1 due to logistical constraints. Therefore, the relation between porewater CH_4 concentrations and CH_4 fluxes were tested separately using linear regression.

The statistical analyses were conducted in R (R core team, 2016), where the random forest analysis was performed using the ‘RandomForest’ package (Liaw and Wiener 2002). Graphs were created using JPM (JMP 2021). All data are shown with their average ± standard deviation.

3 Results

3.1 RQ1: mitigation potential of TSR and the presence of Typha on the GHG emission

3.1.1 Experiment 1: topsoil removal every 5 cm

CH_4 emissions differed over time and with different amounts of TSR, but not between peat types (Fig. 2A; Table S1 and Table S2). The highest CH_4 emissions were found in the 0 cm TSR treatment (overall average ± standard deviation: 395 ± 758 mg CH_4 m^{-2} day^{-1}) and were already 6-times lower with TSR of 5 cm (67 ± 186 mg CH_4 m^{-2}

day^{-1}). CH_4 emissions further decreased to 23 ± 67 mg CH_4 m^{-2} day^{-1} at 10 cm TSR, 23 ± 122 mg CH_4 m^{-2} day^{-1} at 15 cm TSR, and less than 1 mg CH_4 m^{-2} day^{-1} at 20 and 25 cm TSR (Fig. 2A). Emissions peaked after three months for the 0, 5, and 10 cm TSR and gradually declined afterward (Fig. 2A).

CO_2 emissions differed between TSR treatments and over time, but not between peat types (Fig. 2B; Table S3). The highest CO_2 emissions were found in the treatment with 0 cm TSR (overall average ± standard deviation: 6496 ± 9243 mg CO_2 m^{-2} day^{-1}). CO_2 emissions decreased with an increase in TSR: 2655 ± 3798 mg CO_2 m^{-2} day^{-1} with 5 cm, 1967 ± 2468 mg CO_2 m^{-2} day^{-1} with 10 cm, 1309 ± 1685 mg CO_2 m^{-2} day^{-1} with 15 cm, 1423 ± 2469 mg CO_2 m^{-2} day^{-1} with 20 cm, and 617 ± 885 mg CO_2 m^{-2} day^{-1} with 25 cm. Despite water-logged conditions, TSR treatments caused CO_2 emissions to differ by a factor of 10.

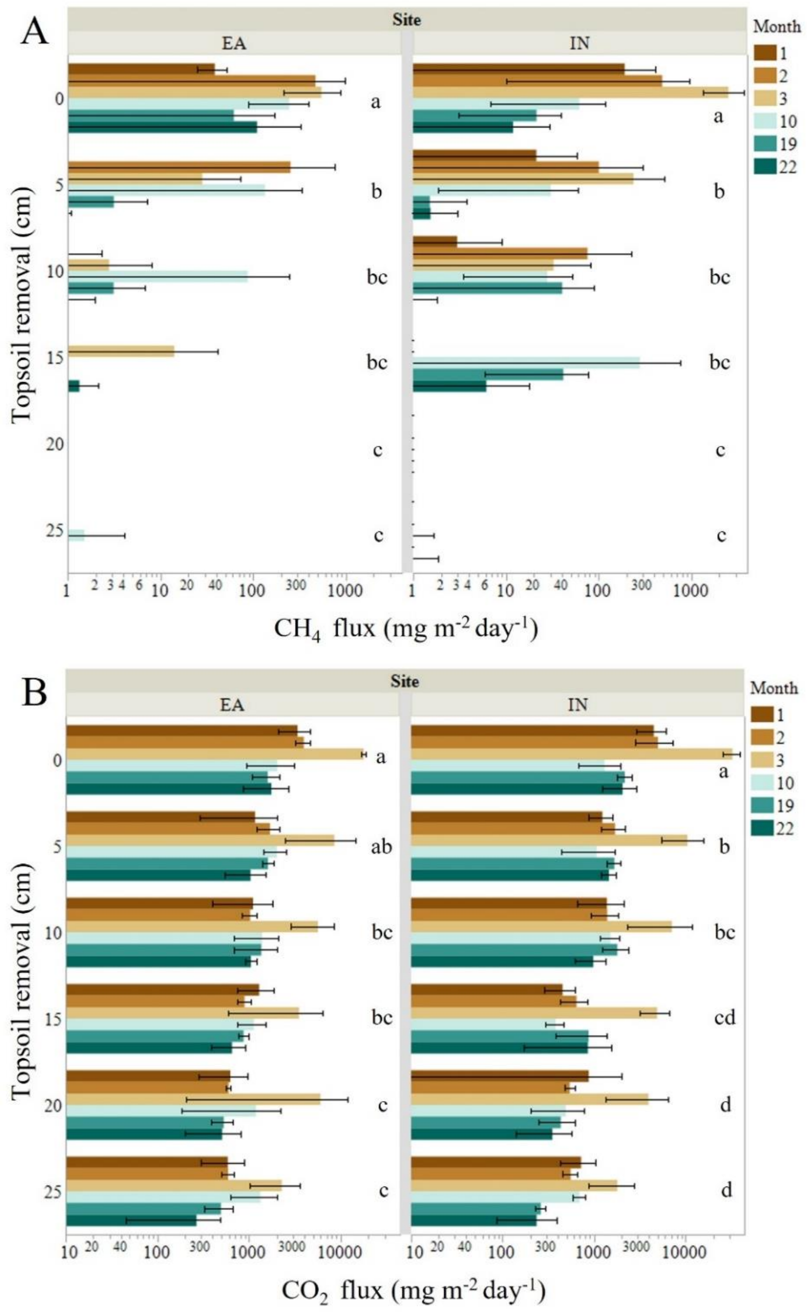

Fig. 2 Emissions of (A) methane (CH_4; mg m^{-2} day^{-1}) and (B) carbon dioxide (CO_2; mg m^{-2} day^{-1}) under water-logged conditions per topsoil removal increment (cm) over time and per peat type. EA = extensively managed, acid peat. IN = intensively managed, near-neutral peat. Note: the x-axes are presented on a logarithmic scale. Bars represent the average and standard deviation ($n = 4$). Colors indicate the time of measurement (months into the experiment). Letters indicate significant differences between TSR depth per peat type ($p < 0.05$). Data from experiment 1.

3.1.2 Experiment 2: interaction between topsoil removal and presence of T. latifolia

CH_4 emissions differed over time, with different amounts of TSR and with the presence or absence of *Typha* (Fig. 3; Table S4 and Table S5). The lowering effect of TSR on CH_4 emissions remained when *Typha* was present. Vegetated mesocosms in combination with TSR revealed the lowest CH_4 emissions (Fig. 3). In the presence of *Typha*, 5 cm TSR significantly reduced CH_4 emissions by ~20 times, from 115 ± 113 mg CH_4 m^{-2} day^{-1} at 0 cm TSR to 6 ± 10 mg CH_4 m^{-2} day^{-1} at 5 cm TSR (Fig. 3; $p < 0.001$). In unvegetated treatments, 5 cm TSR significantly reduced CH_4 emissions by more than 8 times, from 523 ± 276 mg CH_4 m^{-2} day^{-1} at 0 cm TSR to 64 ± 137 mg CH_4 m^{-2} day^{-1} at 5 cm TSR (Fig. 3; $p < 0.001$). There was no further significant decrease in emissions from 5 cm to 15 cm TSR. CH_4 emissions appeared to increase over time, except for mesocosms with *Typha* at 0 cm TSR where emissions appeared to decrease. However, none of these differences were significant (Table S4 and Table S5).

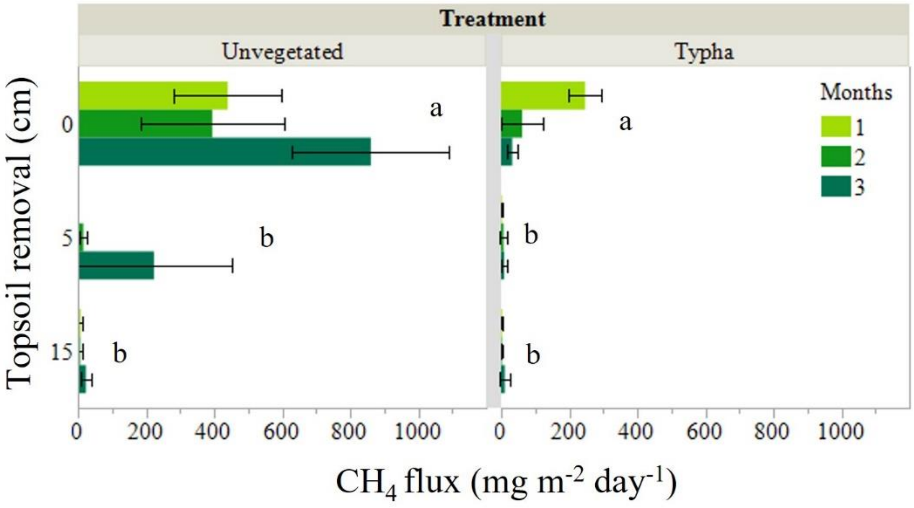

Fig. 3 Methane (CH_4) emissions (mg m^{-2} day^{-1}) per topsoil removal increment (cm). Distinctions have been made over time (months into the experiment, indicated by color) and between treatments (i.e., unvegetated and Typha). Data from experiment 2, where only one peat type (IN) was used. Note: CH_4 fluxes are not shown on a logarithmic scale. Bars represent the average and standard deviation ($n = 5$ for Typha, $n = 3$ for unvegetated). Letters indicate significant differences between TSR depth per vegetation treatment ($p < 0.05$).

3.2 RQ2: effects of TSR and the presence of Typha on nutrient availability

3.2.1 Experiment 1: topsoil removal every 5 cm

Grass and root biomass, our proxy for easily decomposable carbon, differed per TSR treatment and per peat type ($p = 0.004$; Fig. 4, Table S6). Overall, values were higher in the 0 cm TSR treatment and on IN peat (Fig. 4, Table S6).

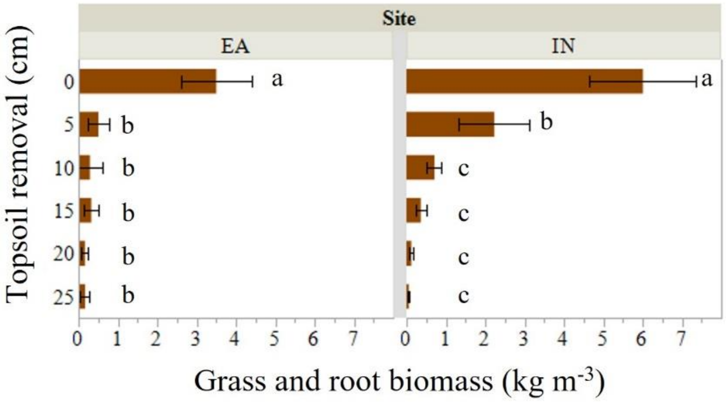

Fig. 4 Grass and root biomass per volume (kg dry weight m^{-3}) per topsoil removal increment (cm) in the extensively managed, acid peat (EA) and in the intensively managed, near-neutral peat (IN). Bars represent the average and standard deviation ($n = 4$). The 0 cm TSR treatment contained both aboveground biomass (leaf and shoot biomass) and belowground biomass (grass roots). Letters indicate significant differences between TSR depth per peat type ($p < 0.05$). Data from experiment 1.

Porewater CH_4, pH, alkalinity, P, and NH_4^+ values differed per peat type, but not porewater Fe and S concentrations (Fig. 5, Table S7, Fig. S1). TSR affected porewater values of CH_4, pH, alkalinity, NH_4^+, Fe, and S, except for P concentrations (Fig. 5, Table S7, Fig. S1). Moreover, porewater values of pH, alkalinity, P, NH_4^+, Fe, and S changed over time, except for CH_4 concentrations (Fig. 5, Table S7, Fig. S1).

CH_4 porewater concentrations declined with increasing TSR (Fig. 5A, Table S7). The highest CH_4 concentrations were found in the treatments with 0 cm TSR (EA = 665 ± 500 µmol L^{-1}; IN = 1624 ± 1218 µmol L^{-1}). The 5 cm TSR treatment lowered CH_4 porewater by 2 and 12-times (EA = 223 ± 312 µmol L^{-1}; IN = 135 ± 236 µmol L^{-1}). The decrease in pH with increasing TSR was more pronounced on EA peat, which lines up with the alkalinity being lower in EA at increased TSR compared to IN (Fig. 5B and C, Table S7). Both P and Fe concentrations accumulated over time, showing higher concentrations in month 10 (Fig. 5D, Fig. S1B, Table S7). Contrary to the other elements where concentrations decreased with increased TSR, the concentrations of S species (oxidized, reduced, and elemental sulfur) increased overall (Fig. S1C, Table S7).

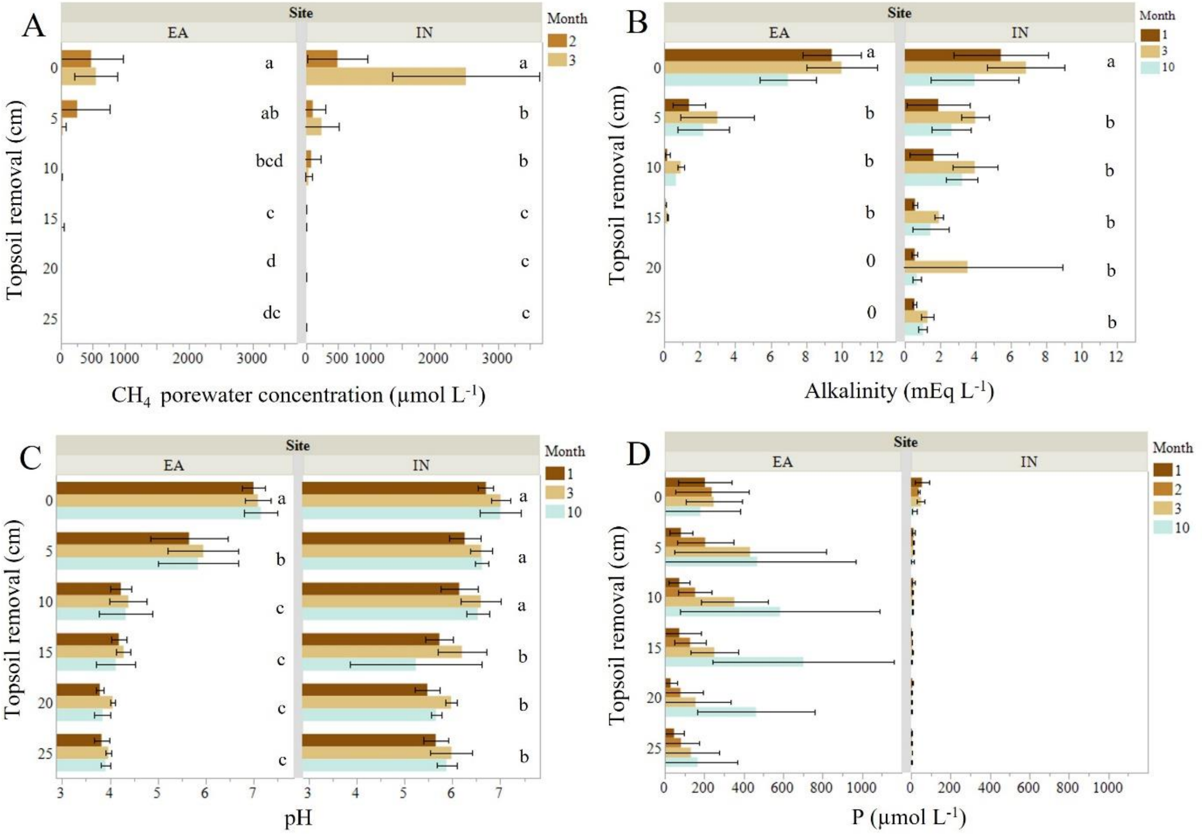

Fig. 5 Porewater chemistry results of (A) methane (CH_4; μmol L^{-1}), (B) alkalinity (mEq L^{-1}), (C) pH, and (D) phosphorus (P; μmol L^{-1}) per topsoil removal increment (cm) over time and per peat type. EA = extensively managed, acid peat. IN = intensively managed, near-neutral peat. Bars represent the average and standard deviation (*n* = 4). Colors indicate the time of measurement (months into the experiment). Letters indicate significant differences between TSR depth per peat type ($p < 0.05$). Data from experiment 1.

3.2.2. Experiment 2: interaction between topsoil removal and presence of T. latifolia

Peat porewater chemistry was also affected by the presence of plants. Overall, porewater CH_4 concentrations were about 15 times lower in *Typha* treatments (48 ± 47 µmol L^{-1}) than in unvegetated treatments (729 ± 386 µmol L^{-1}; $p < 0.001$; Fig. 6A). CH_4 concentrations were higher in the 0 cm TSR treatments than 5 or 15 cm, with or without *Typha* (Fig. 6A). The addition of *Typha* and the different TSR treatments altered pH, alkalinity, P, NH_4^+, and Fe values, but not S concentrations (Fig. 6, Fig. S2, Table S8). Only pH, NH_4^+, Fe, and S values changed over time (Fig. 6, Fig. S2, Table S8). We observed decreased porewater NH_4^+, P, and Fe concentrations in the *Typha* treatments (Fig. 6, Fig. S2, Table S8). The effect of TSR, independent of the presence of *Typha*, was observed for NH_4^+ and P, with higher concentrations in the treatments with 0 cm TSR. In unvegetated treatments, TSR had a positive effect on Fe concentrations ($p < 0.001$) (Fig. S2B), while in both *Typha* and unvegetated treatments, S concentrations increased with increasing TSR ($p < 0.001$) (Fig. S2C).

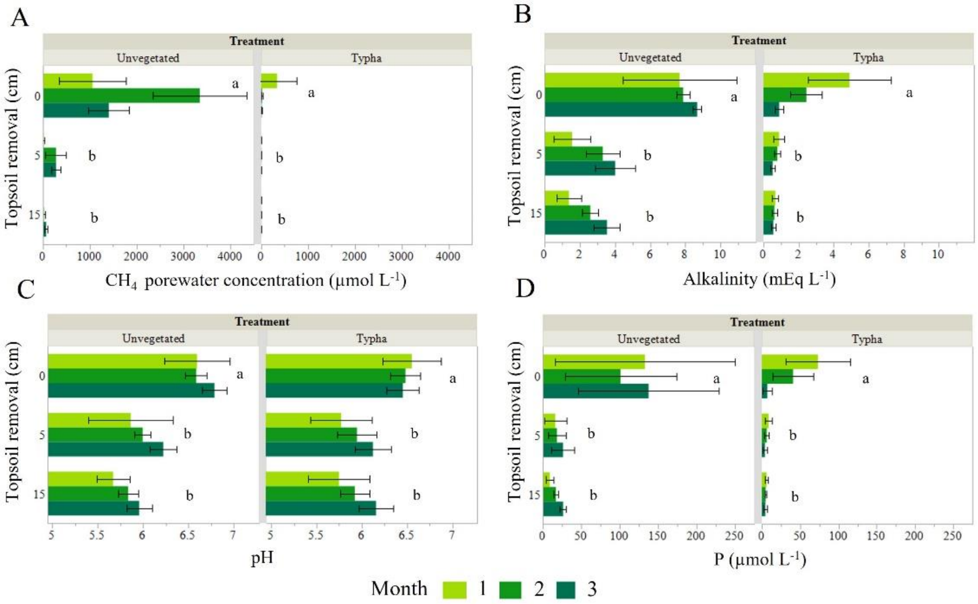

Fig. 6 Porewater chemistry results of (A) methane concentration (CH_4; µmol L^{-1}), (B) alkalinity (mEq L^{-1}), (C) pH, and (D) phosphorus concentration (P; µmol L^{-1}) per topsoil removal increment (cm). Distinctions have been made over time (months into the experiment, indicated by color) and between treatments (i.e., unvegetated and Typha). Data from experiment 2, where only one peat type (IN) was used. Bars represent the average and standard deviation (*n* = 5 for Typha, *n* = 3 for unvegetated). Letters indicate significant differences between TSR depth per vegetation treatment ($p < 0.05$).

3.3 RQ3: main drivers of CH_4 emissions

For experiment 1, the random forest analysis showed that cumulative root biomass and porewater alkalinity were the most important determinants of CH_4 emissions (Fig. 7A). For experiment 2, porewater alkalinity and P concentration mostly explained CH_4 emissions (Fig. 7B). Furthermore, porewater CH_4 concentration showed a positive correlation with CH_4 flux for experiment 1 (Fig. S3; EA: $R^2 = 0.293$, $p < 0.0001$; IN: $R^2 = 0.402$, $p < 0.0001$) and experiment 2 (Fig. S3; *Typha*: $R^2 = 0.64$, $p < 0.0001$; unvegetated: $R^2 = 0.16$, $p = 0.0157$).

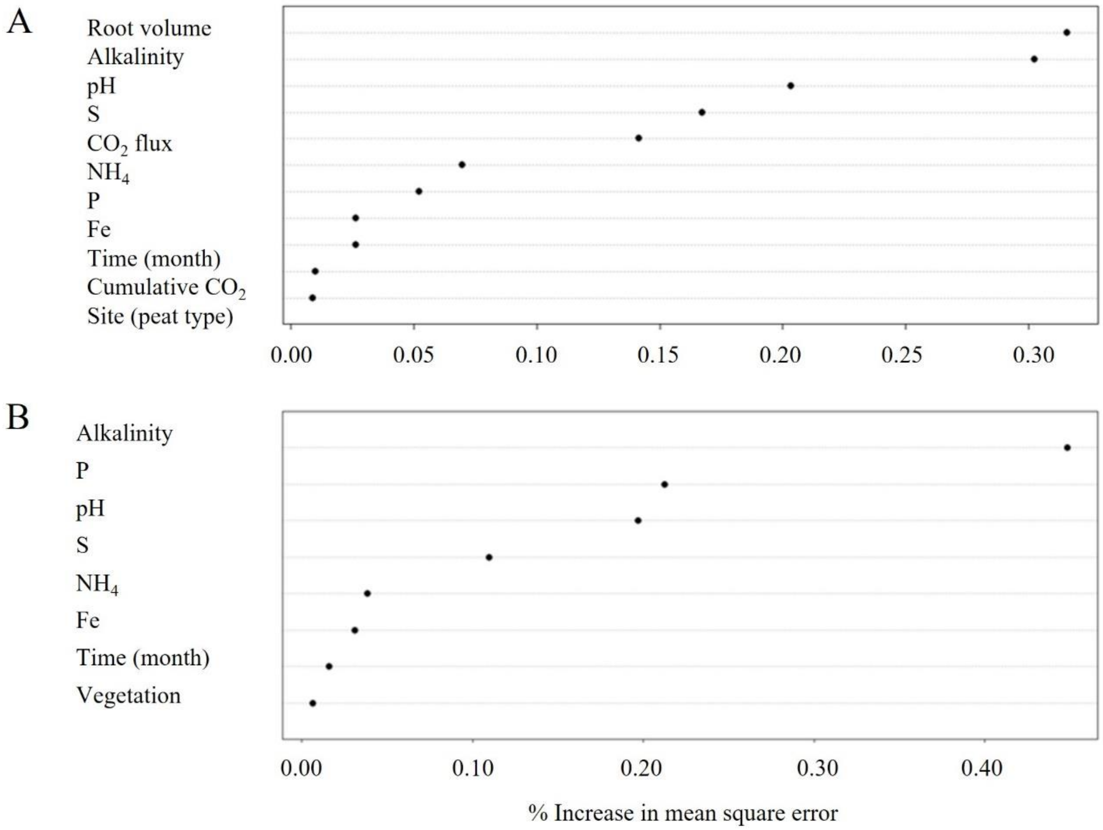

Fig. 7 Importance of different variables in predicting CH_4 emissions in the Random Forest analysis for experiment 1 (A): MSE = 0.28, $R^2 = 0.75$, and experiment 2 (B): MSE = 11381, $R^2 = 0.75$. Cumulative root volume was not included for experiment 2 due to a lack of data. For experiment 1, we included measurements from months 1, 3, and 10 only, since not all predictors were measured at other times.

4 Discussion

We showed that TSR has a strong effect on the availability of nutrients, (labile) carbon, and minerals, and the consequent emission of CH_4 and CO_2 from rewetted agricultural peat. Specifically, the highest CH_4 emissions occurred after three months with 0 cm TSR. Surprisingly, 5 cm TSR and 10 cm TSR largely reduced these high GHG emissions post rewetting. Moreover, with increasing amounts of TSR, there was no additional significant reduction in GHG emissions. Furthermore, climate benefits from shallow TSR prevailed in mesocosms planted with *T. latifolia*, a wetland plant associated with high CH_4 emissions in wetlands. However, we stress that our vegetation experiment only lasted for three months when roots potentially allow for minimal oxidation of submerged peat, while root exudates and easily degradable plant litter of *Typha* can potentially boost CH_4 production and thus emissions over time. Optimal TSR depth with the goal to reduce nutrient availability requires removal of at least 5 cm, while the inclusion of plants reduces the depth of peat that should be removed. Thus, as optimal TSR depth can differ with the goal of rewetting the peatland, clear goal setting is vital to determine optimal TSR depth. Nevertheless, our results suggest that the standard 30-60 cm of TSR is not always necessary to gain climate benefits nor for nutrient reduction.

4.1 The mitigation potential of minimal TSR and Typha presence on GHG emissions

We show that a mere 5 to 10 cm of TSR can sufficiently reduce CH_4 and CO_2 emissions from rewetted agricultural peatlands. On average for the two peat types used in this study, we show that 5 cm of TSR reduces CH_4 emissions by 1.9 tons of CH_4 ha^{-1} yr^{-1} and an additional 5 cm of TSR reduces emissions only further by 0.2 tons of CH_4 ha^{-1} yr^{-1}. Although TSR is already known to reduce GHG emissions, previous studies applied at least 25 cm TSR (Harpenslager et al. 2015; Zak et al. 2018; Huth et al. 2020). Therefore, our results suggest that the standard practice of removing 30 to 60 cm of peat (Allison and Ausden 2004; Huth et al. 2020) is exceeding what would be required from a climate change mitigation perspective. Rewetting alone reduced CO_2 emissions, which agrees with previous studies (Wilson et al. 2016b; Günter et al. 2020; Huth et al. 2021). Important to consider that we did not include controls without waterlogging, where CO_2 emissions would have been higher. However, the rewetting of peatlands is found to favor CH_4 fluxes at the beginning (Wilson et al. 2009; Evans et al. 2021), while CH_4 emissions decrease in the long-term (Günther et al. 2020). In this study, CH_4 emissions rose for three months followed by a marked lowering in treatments where TSR was small or absent.

Besides the impact of TSR directly on the local environment and indirectly on costs, the removed peat needs to be considered in the carbon balance of rewetted peat soils. Huth et al. (2021) found that TSR is a sustainable option for climate mitigation even when the carbon losses in the removed topsoil were considered. However, minimizing carbon export is critical and lines up with our findings that 5 cm TSR already represents a great gain in climate mitigation.

Even though wetland vegetation is known to enhance CH_4 emissions by the shunt effect, transporting CH_4 from the soil to the atmosphere (Fritz et al. 2011; Agethen et al. 2018; Huth et al. 2020), our data show that climate gains by TSR are not offset by the presence of *Typha* in the first phase after rewetting. In our study, the presence of *Typha* decreased CH_4 emissions to the atmosphere, most likely induced by rhizosphere oxidation. Similar results were found in other short-term mesocosm experiments (Vroom et al. 2018) and for a broad range of wetland plants (Kao-Kniffin et al. 2010). However, over time, higher CH_4 *in situ* emissions in peatlands with the presence of *T. latifolia* are observed (Wilson et al. 2009). This suggests that *Typha* may be planted directly after rewetting but should be harvested or removed before decay starts.

4.2 Effect of minimal TSR and Typha presence on nutrient availability

In peatland restoration projects, TSR is also a promising practice to reduce internal eutrophication and pollution downstream by reducing, for example, P mobilization (Allison and Ausden 2004; Harpenslager et al. 2015; Zak et al. 2017; Zak et al. 2018). This reduction in nutrient availability can even be achieved with the minimal TSR approach, as we found that porewater NH_4^+ and Fe concentrations reduced significantly with 5 cm TSR. The presence of *T. latifolia* further decreased the porewater concentrations of NH_4^+ and Fe. Although we did not find a clear reduction in porewater P concentration with minimal TSR, the presence of *T. latifolia* did lower P mobilization. Peat type also had an influence on the effect of minimal TSR: near-neutral peat lowered P mobilization compared to the more acid peat type, but Fe concentrations only reduced on near-neutral peat with more than 15 cm TSR.

This suggests that, depending on peat pH, more or less TSR might be required and that nutrient-specific goals will be needed to reduce efforts on TSR while simultaneously reducing internal eutrophication and nutrient leaching. This is especially relevant for S since we found that porewater S concentrations only increased with minimal TSR, and peat type and vegetation had no influence. Our results further suggest that vegetation growth for a short period of time after rewetting may be a solution to limit nutrient availability on near-neutral peat, which is in line with earlier findings on near-neutral and acid peat (Vroom et al. 2022).

4.3 Main drivers of CH_4 emissions

Various factors are known to affect CH_4 emissions, e.g., substrate availability (labile carbon), pH, alkalinity, porewater (micro)nutrients, and redox potential. These mechanisms can be categorized as CH_4-production stimulating (e.g., pH and alkalinity), CH_4-production limiting (e.g., SO_4^{2-}), or CH_4 consuming (e.g., anaerobic CH_4 oxidation) (Table 1). Porewater alkalinity was strongly associated with CH_4 emissions in both experiments and to a lesser extent porewater pH. Minimal TSR decreased both porewater alkalinity and pH. Studies performed in peatlands indicate the suppression of CH_4 production in acid conditions (Williams and Crawford 1984; Smolders et al. 2002; Ye et al. 2011) and report an optimal pH for methanogenesis between 6.0 and 7.0 (Williams and Crawford 1984; Blodau 2002; Nilsson and Öquist 2009). Therefore, the drop in pH due to TSR may have affected CH_4 fluxes, but it is unlikely to be the dominant factor. Acid and poorly buffered conditions may also favor peat accumulation, meaning that low alkalinity values, usually observed in less reactive systems, may hamper mineralization (Roelofs 1991; Smolders et al. 2006). This is supported by the simulated CH_4 production when bicarbonate is added to a system (Harpenslager et al. 2015). After inundation alkalinity (bicarbonate) is generated internally due to the anaerobic mineralization of labile organic matter (van der Heide et al. 2010). Since porewater elements and nutrients seemed to be only loosely associated with CH_4 emissions, it is suggested that substrate availability seemed to be the dominant controller of methanogenic activity in our study.

We found that cumulative root biomass, used here as a proxy for easily decomposable or labile carbon, was also highly associated with CH_4 emissions. Although root biomass data was not available for experiment 2, we assume that the rooting depth of grasses remained similar over the course of two years in the same paddock sampled for experiment 1. Similarly, Pypker et al. (2016) found that increased plant productivity observed in summer favored CH_4 production, due to the enhanced input of labile carbon. The top layer of the peat, which is typically oxic, receives most of the labile carbon (Artz 2009; Hahn-Schöfl et al. 2011; Hahn et al. 2015). Especially decaying aboveground and belowground biomass have been associated with peak CH_4 emissions (Hahn-Schöfl et al. 2011; Sibiya and Muzenda 2014; Franz et al. 2015). A similar result was found by Helfter et al. (2022), where the higher green vegetation and aboveground biomass during the summer resulted in higher CH_4 emissions. Noteworthy, Girkin et al. (2018) showed that the composition of root exudates can be more important as regulators of CO_2 and CH_4 production than their input rate. In addition, when roots decay (i.e., loss of labile carbon), a rapid turnover to more recalcitrant compounds occurs (Artz 2009; Glaser and Chanton 2009; Hahn-Schöfl et al. 2011). Accordingly, we argue that the reduction of CH_4 emissions observed with TSR is mainly related to the removal of labile carbon from the system. The substrate argument is further supported by the initial increase followed by a decrease in GHG emissions over time when less than 15 cm of topsoil was removed. Similarly, the highest CO_2 emissions arise with 5 cm TSR suggesting high carbon turnover. In top layers, methanogenic and heterotrophic microorganisms could use the large carbon pool, whereas deeper TSR would result in a cut-off from the labile carbon resulting in suppression of CH_4 emissions (Segers 1998). The CH_4 emissions observed in the treatments with deeper TSR are probably related to low to very low substrate availability limiting methanogen activity deeper in the profile (Yrjälä et al. 2011; Urbanová and Bárta 2016).

Although low amounts of CH_4 are still being emitted after almost two years, we expect that high emissions would occur if a new pool of fresh carbon enters the system, e.g., as a consequence of plant or algae growth (Hahn-Schöfl et al. 2011; Harpenslager et al. 2015). That could be an important reason to remove the nutrient-rich layer rather than only the top 5 cm, resulting in largely lower productivity and, consequently, biomass production and labile organic matter. However, we also showed that 5 cm TSR reduced nutrient concentrations in the IN peat, and therefore, we argue that an assessment of labile carbon in the top peat layer prior to peat treatment (i.e., TSR and rewetting) can save resources and reduce environmental impacts. This assessment can make use of porewater CH_4 concentrations since it showed positive correlations with CH_4 emissions on both peat types and with and without the presence of *T. latifolia*. In addition, both CH_4 emissions and CH_4 porewater were similarly affected by TSR. This suggests that the effects we observe on emissions are likely the result of increased CH_4 production. In turn, differences in the transport mechanism and CH_4 oxidation in the water layer are less likely to explain the TSR effect.

Table 1. Summary of relevant CH_4 flux mechanisms. The table was limited to the elements investigated in the present study.

Category	**Element(s) involved**	**Mechanism**	**Proof**	**Supporting refs**
CH_4-production stimulating	pH	Optimal production at pH 6.0 to 7.0	Similar trend to CH_4 flux (i.e., pH decreased with increasing TSR)	1, 2, 3
	Alkalinity	Stimulates mineralization	Similar trend to CH_4 flux (i.e., alkalinity decreased with increasing TSR)	4, 5, 6
	Labile C	Substrate for methanogenesis	Similar trend to CH_4 flux (i.e., labile C decreased with increasing TSR)	2, 6, 7, 8, 9
	NH_4^+	Increases mineralization of labile carbon and limits CH_4 oxidation by binding to receptors of methanotrophs	Similar trend to CH_4 flux (i.e., NH_4^+ reduced with increasing TSR)	10, 11, 12, 13
	Fe^{3+}	Increased mobilization results in organic matter breakdown	Increasing concentrations over the first three months as the CH_4 fluxes	14
CH_4-production limiting	SO_4^{2-}	Competitive advantage SO_4^{2-} over CO_2 reducers and sulfide toxicity	Opposite trend to CH_4 flux (i.e., S increased with increasing TSR)	15, 16, 17, 18, 19
CH_4-consuming	SO_4^{2-} and Fe^{3+}	Enables anaerobic CH_4 oxidation	Different trends compared to CH_4 flux (i.e., S increased with increasing TSR, and Fe concentrations were not affected as CH_4 by TSR)	20, 21, 22, 23, 24
Ambiguous	P	Stimulates microbial growth (producers and oxidizers)	P concentrations were not affected as CH_4 by TSR.	25, 26, 27
References 1 Williams and Crawford 1984; 2 Smolders et al. 2002; 3 Ye et al. 2011; 4 Roelofs 1991; 5 Smolders et al. 2006; 6 Harpenslager et al. 2015; 7 Segers 1998; 8 Conrad 1999; 9 Conrad 2007; 10 O'neill and Wilkinson 1977; 11 King and Schnell 1994; 12 Bodelier and Laanbroek 2004; 13 Currey et al. 2010; 14 Emsens et al. 2016; 15 Maillacheruvu et al. 1993; 16 Gauci et al. 2004; 17 Gauci et al. 2005; 18 Blodau et al. 2007; 19 De Jong et al. 2020; 20 Smemo and Yavitt 2007; 21 Zhu et al. 2012; 22 Wegener et al. 2015; 23 Ettwig et al. 2016; 24 Cai et al. 2018; 25 Schrier-Uijl et al. 2011; 26 Medvedeff et al. 2014; 27 Nijman et al. 2022				

5 Conclusions and implications for management

The present study shows that i) there is a large variation in GHG emissions depending on TSR and time since rewetting; ii) 5 to 10 cm TSR may be sufficient to greatly reduce GHG emissions upon rewetting; iii) these climate benefits are not offset by introducing wetland vegetation (i.e., *T. latifolia*), which in turn further reduces emission in the first period after rewetting and bypasses CH_4 emission peaks three months after rewetting; and iv) 5 cm TSR may not be enough to reduce nutrient availability. These results indicate that costs can be reduced by minimizing TSR prior to peatland rewetting (e.g., transport, labor, machines), when reducing GHG emissions and minimizing soil subsidence is the main goal. It is of paramount importance that the area is not ploughed, as this homogenizes the vertical profile. In this light, current standard TSR practices of 30-60 cm are not required from a climate perspective but will, in many cases, be necessary from a nutrient perspective (Van Diggelen et al. 2020). Therefore, clear targets need to be set before determining TSR depth. Furthermore, as GHG emission after rewetting is largely driven by labile carbon, we suggest rapid rewetting after TSR to prevent the establishment of vegetation that enriches the topsoil with labile carbon (e.g., plant litter, roots, exudates, aboveground biomass). Further research is needed to develop a tool to easily predict optimal TSR depth to reduce GHG emissions for all types of peatlands (e.g., differing in nutrient/mineral status) in temperate and boreal climates.

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Statements and Declarations

Acknowledgments

We are grateful to Raoul Luijten, Reinder Nouta, Peter Cruijsen, Roy Peters, and Tom Heuts for their help during the sampling, emission measurements, and laboratory analysis. We thank Sebastian Krosse of the General Instrumentation for ICP analysis. We thank Karel van Houwelingen, KTC Zegveld and Romke Kinderman (Bûtefjild, Better Wetter) for the permission to take soil cores on their land.

Funding

C.F. was funded by Wet Horizons (Horizon Europe GAP-101056848). C.C.F.B. received funding from NWE-Interreg Carbon Connects.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Data Availability

Data will be stored in DANS-EASY upon acceptance.