The climate benefits of topsoil removal and Sphagnum introduction in raised bog restoration

Vytas Huth1,2†, Anke Günther1†, Anna Bartel3, Cordula Gutekunst1, Stefanie Heinze4, Bernd Hofer5, Oona Jacobs1, Franziska Koebsch1, Eva Rosinski5, Claudia Tonn1, Karin Ullrich4, Gerald Jurasinski1

Many raised bogs in Central Europe are in an unfavorable state: drainage causes high emissions of carbon dioxide (CO2) and nitrous oxide (N2O), while rewetting may result in high methane (CH4) emissions. Also, the establishment of typical bog species is often hampered during restoration. Measures like topsoil removal (TSR) or introduction of target vegetation are known to improve restoration success in other systems, but experiences on bogs after long-term agricultural use are scarce and their climate effects including carbon losses from TSR are unknown. In a field trial in north-western Germany, consisting of seven plots (intensive grassland, IG, and six restoration approaches), we explored the effects of rewetting, TSR and Sphagnum introduction on greenhouse gas (GHG) emissions. We measured GHG fluxes to obtain two-year GHG budgets and applied a radiative forcing model to assess the time-dependent climate effects. Existing uncertainty of decomposition processes in the translocated topsoil has been incorporated by different topsoil accounting scenarios. According to our data, rewetting alone reduced CO2 emissions by approximately 75% compared to IG, but substantially increased CH4 emissions. After TSR and rewetting, on-site CO2 emissions were close to zero or, with Sphagnum introduction, net negative while CH4 emissions remained very low. The climatic warming effect of TSR including C export becomes less climate warming than rewetting nutrient-rich peatlands after a few decades. For raised bog restoration, we therefore recommend a TSR sufficient to achieve nutrient-poor and acidic conditions needed for rapid Sphagnum establishment.

Key words: carbon dioxide, climate warming, methane, peatland, raised bog, restoration management, rewetting, Sphagnum introduction

Implications for Practice
• Topsoil removal (TSR) is a viable option when rewetting nutrient-rich temperate bogs for climate mitigation, even when the additional climate warming from carbon export in the topsoil is considered.
• For restoration of raised bog habitats after intensive agricultural use, the depth of TSR should be adapted to local conditions to minimize carbon export while establishing nutrient-poor and acidic conditions needed for rapid Sphagnum establishment.

Introduction
Pristine peatlands provide important ecosystem services such as carbon (C) sequestration and suitable habitats for rare biota (Verhoeven 2014). Although the value of European peatlands has been acknowledged through a variety of policies, many have lost their ecosystem functions caused by land use (Andersen et al. 2017).

While agriculturally used raised bogs cover large areas in regions like Western and Central Europe (Moore 2002; Tiemeyer et al. 2016), few have been restored (Andersen et al. 2017). Therefore, bog restoration has been studied mainly in former peat extraction areas (Wilson et al. 2009; Renou-Wilson et al. 2018). Drained, agriculturally used bogs have become carbon dioxide (CO2) sources through accelerated peat oxidation. In order to restore the C sink function, restoration management needs to minimize CO2 emissions and quickly establish peat-forming vegetation. Rewetting is an effective measure to reduce CO2 emissions from peatlands (Komulainen et al. 1999; Nugent 2016).
et al. 2018). Further, the removal of the uppermost, eutrophic, degraded peat layer (“topsoil removal,” TSR) effectively reduces methane (CH4) emissions after rewetting (Huth et al. 2020) because it provides an “ecosystem set-back” from soils with compromised physical functioning and nutrient status (Brouns et al. 2014) to more pristine conditions (Patzelt et al. 2001; Emsens et al. 2015). Also, the previously cultivated vegetation can effectively be removed by TSR (Klimkowska et al. 2010), facilitating the establishment of peat-forming vegetation (Patzelt et al. 2001; Emsens et al. 2015). However, bare peat may take decades to be fully reclaimed by target vegetation (Renou-Wilson et al. 2018). In extracted peat bogs, the active introduction of Sphagnum spp. (peat moss) fragments can accelerate the establishment of typical bog vegetation and “kick-start” C sequestration (Nugent et al. 2018; Quinty et al. 2020).

Similar to peat extraction (Cleary et al. 2005), the amount of C removed from the ecosystem by TSR and the rate at which removed topsoil decomposes potentially determines the overall climatic effect of the restoration approach. To our knowledge, the combined climatic effects of soil greenhouse gas (GHG) fluxes and removed topsoil have never been assessed before. Therefore, we installed a field trial with controlled water management to study the climatic effects of different restoration approaches with and without TSR and Sphagnum introduction for a raised bog with previous intensive grassland use. Here, we present (1) the effects of TSR and Sphagnum introduction on on-site GHG emissions during the first 2 years of restoration, and (2) an assessment of the climatic effects of six restoration approaches including C losses from TSR using a radiative forcing model (Günther et al. 2020) and different topsoil decomposition scenarios.

Methods

Study Site

The study site (lat 53°15’25’’N, long 8°14’54’’E, 1 m a.s.l.) is located in northwestern Germany as part of the Atlantic biogeographical region (Fig. 1). The regional climate is humid with a mean annual temperature of 9.96°C and precipitation of approximately 817 mm (1991–2020, DWD, grid product). The study site had been drained and used as grassland for decades. Immediately before the field experiment was installed, the grassland had been subject to a two/three-cut regime with late grazing (approximately 4 livestock units per hectare) and fertilization (N-equivalent of 150 kg/ha).

After long-term drainage, the topography of the study site is characterized by regular linear depressions that mark the location of drainage tubes. The topsoil is compacted and rich in N and P with the upper 10 cm containing 0.5 ± 0.1 kg/m² and 9.4 ± 1.8 g/m², respectively (Huth et al. 2019). Prior to experiment installation, typical species of intensively used temperate grassland vegetation were removed by topsoil removal (TSR) and introduced Sphagnum (Sphagnum spp.), and/or mowing. The aerial view shows the study site on 18 April 2018.

Figure 1. The study site in northwestern Germany with the location of the status-quo plot (black dashed rectangle) characterized by intensive grassland (“IG”) and the restoration plots (black rectangles) including the spatially randomized chamber collars (white circles). The individual restoration plots either retained their original surface (“OS”) or were subjected to topsoil removal of approximately 30 cm ("TSR30") or approximately 60 cm depth ("TSR60"). Sphagnum introduction ("+Sphagnum"), and/or mowing ("+mowing"). The aerial view shows the study site on 18 April 2018.
grasses dominated the study site, while species of flood waters occurred in the wet and temporarily inundated depressions (Huth et al. 2019).

**Study Design**

During spring 2017, seven plots of approximately 8 × 24 m (Fig. 1) were installed in the study site. The status-quo plot is managed mimicking the previous land use (intensive grassland—“IG,” Table 1). The plots for the six restoration approaches are surrounded by sheet piles to ensure rewetting for the experiment. They are equipped with a controlled water management system that is set at water tables of 10–0 cm below mean surface height of each plot. Thus, at plots with the original topography containing surface depressions (original surface—“OS”), approximately one third will be permanently inundated. The six restoration approaches consist of different combinations of measures found in restoration practice (Table 1). The mean annual water table of IG is lower than 30 cm below surface and can fall below 1 m during summer.

*Sphagnum* spp. fragments originated from a nearby Sphagnum farming site (Günther et al. 2017/2018). Dominant species in the donor material were *Sphagnum fallax* (H. Klinggr.) H. Klinggr., *Sphagnum palustre* L., *Sphagnum papillosum* Lindb., *Sphagnum cespitatum* Ehrh. ex Hoffm., and *Drosera rotundifolia* L. Harvested *Sphagnum* biomass was manually shredded into smaller pieces and spread at a thickness of roughly 1–5 cm.

Prior to the installation of the field trial, soil sampling to estimate dry bulk density and C content was performed in five depths (approximately 10, 30, 60, 90, and 150 cm below surface) at four locations on the border of each of the planned plots (Huth et al. 2019). Here, C export by TSR is calculated as the mean (±1 SE) cumulative C stock down to 30 (TSR30, TSR30 + Sphagnum) or 60 cm (TSR60, TSR60 + Sphagnum) of four locations per plot.

**Greenhouse Gas Measurements**

In each plot three GHG sampling locations were chosen randomly using the R package *rgos* (Bivand & Rundel 2017; Fig. 1). PVC collars (0.8 m × 0.8 m × 0.2 m) were inserted permanently into the soil (approximately 10 cm) on 1 June 2017. However, we ensured that in each of the plots with the original surface, at least one collar was placed in a depression and one in the higher areas, so that the maximum variation of surface topography was covered (Huth et al. 2020). We measured GHG fluxes biweekly from 24 September 2017 to 25 September 2018 (year 1) and from 25 September 2018 to 25 September 2019 (year 2), totaling 60 field days. During harvest events at IG and OS+mowing, we measured CO₂ fluxes before and after mowing. Opaque and transparent closed chambers (0.5 m height) were operated in non-steady state (Livingston & Hutchinson 1995).

GHG concentrations within the chambers were determined with infrared gas analyzers (CO₂ and CH₄: GasScouter G4301, Picarro, U.S.A and CO₂: LI-820, LI-COR, U.S.A.) and measurement durations of at least 180 seconds. In addition, chamber headspace and soil temperatures at approximately 5 cm depth were recorded with thermocouples. Transparent chambers were equipped with a quantum sensor (Indium Sensor, Germany) to record photosynthetic active photon flux density (PPFD) during gas measurements.

N₂O concentrations were sampled with evacuated vials (12 mL, Labco, UK) and opaque chambers. Per 1-hour chamber placement, gas samples were taken every 20 minutes. Gas samples were analyzed for N₂O concentration by a gas chromatograph (GC 2010, Shimadzu, Japan) equipped with an electron capture detector.

**Flux Estimation**

Fluxes (reported according to the atmospheric sign convention) were calculated using the packages *flux* (Jurasiński et al. 2014) and *mblm* (Komsta 2013) for R (R Core Team 2020). We fitted a median-based linear model to the CO₂ and CH₄ concentration data using the function *mblm* (Komsta 2013) and a simple linear regression to N₂O concentration data. The slope of the resulting model (dc/dt) was used to calculate the flux according to the following equation:

\[
\frac{dc}{dt} = \frac{M}{RTA} \frac{dp}{dt} \times 10^6
\]

where M is molar mass of the gas, p is partial air pressure (101,300 Pa), V is volume of the chamber (m³), R is the gas constant (8.314 m³·Pa·K⁻¹·mol⁻¹), T is temperature (K), and A is the area of the measured surface (m²). Following the maximum CH₄ uptake (−0.3 mg m⁻²·h⁻¹) found for any ecosystem (Hütsch 2001), we discarded one flux indicating an uptake greater than −0.5 mg m⁻²·h⁻¹.

**Table 1.** Management measures of the seven plots (status quo and six restoration approaches) of the field trial.

| Plot name          | Management measures                                           |
|--------------------|---------------------------------------------------------------|
| IG                 | Three-cut regime with an N-fertilization equivalent of 150 kg/ha mimicking the previous land use |
| OS                 | Rewetting at original surface and free succession              |
| OS+mowing          | Rewetting at original surface with regular (two-cut) biomass harvesting |
| TSR30              | Rewetting after topsoil removal of on average 30 cm and free succession |
| TSR30 + Sphagnum   | Rewetting after topsoil removal of on average 30 cm and introduction of *Sphagnum* spp. fragments covered with a straw layer |
| TSR60              | Rewetting after topsoil removal of on average 60 cm and free succession |
| TSR60 + Sphagnum   | Rewetting after topsoil removal of on average 60 cm and introduction of *Sphagnum* spp. fragments covered with a straw layer |
Environmental Parameters for CO₂ Gap Filling

An on-site weather station recorded half-hourly air temperature and PPFD. Based on the air temperature recordings, we calculated the effective temperature sum (ETI) as a proxy for vegetation development over the year. Following Günther et al. (2017/2018), we defined ETI as the slope of the curve of the effective temperature sum (>5°C). In each plot, soil temperature at approximately 5 cm depth was logged continuously (HOBO Pendant, Onset, U.S.A.). We measured vegetation height biweekly (and pre- and post-mowing in IG and OS + mowing) at five locations per GHG collar. We then averaged vegetation height per collar as input variable for CO₂ models and per plot to create half-hourly records via linear interpolation for gap filling.

Estimation of Annual GHG Budgets

We used artificial neural networks (ANNs) to produce half-hourly time series of CO₂ fluxes to estimate annual CO₂ budgets. The ANNs deployed a backpropagation algorithm and were set up with the R package neuralnet (Fritsch et al. 2019). For each plot and year, 100 ANNs (two hidden layers with three and two nodes, respectively) were trained separately, each time randomly using 80% of the measured fluxes and environmental input data to account for uncertainty related to discontinuous flux measurements. ANNs were validated with the remaining 20% of the measured fluxes, yielding determination coefficients ranging from 70 to 85%. ANNs and half-hourly environmental data were used to calculate 100 time series of half-hourly CO₂ fluxes for each plot and year, from which we calculated the mean annual CO₂ sum ± 1 SE.

We estimated annual CH₄ and N₂O budgets for each collar from all possible combinations of the time series data omitting two measurements (Huth et al. 2020). From the resulting distribution of budgets per collar, we calculated the mean ± 1 SD. The reported annual budgets per plot represent the means of the three collars ± their propagated SDs.

Radiative Forcing of GHG Emissions and C Export

To evaluate the combined effects of the measured short-lived (CH₄) and long-term (CO₂, N₂O) GHGs for the different approaches we calculated the radiative forcing over time following Günther et al. (2020). We assumed that the long-term on-site emissions would correspond to the average of the two studied years. Further, we compared six topsoil decomposition scenarios: (1) all C in the removed topsoil is immediately released as CO₂ in the first year after rewetting (“ts immediate”) representing the current standard methodology for accounting peat extraction in national GHG inventories (IPCC 2006); (2–5) the C is released at annual decomposition rates of 25, 10, 5, and 1% (e.g. “ts_lperc”) representing a range of realistic peat decomposition in horticultural and agricultural after use (Cleary et al. 2005); and (6) no accounting of the removed C (“noacc”) as a reference. Because peatland GHG emissions can be very site-specific (Tiemeyer et al. 2016), we repeated the modeling using IPCC land use classes for each plot and corresponding emission factors from the IPCC wetlands supplement (IPCC 2014) for the on-site emissions and combined them with the C amounts removed by TSR from the field experiment (Table 2).

Statistics

All analyses were performed using R 3.6.3 (R Core Team 2020). Plots were compiled using the R package ggplot2 (Wickham 2009).

Results

Field-Trial and Environmental Conditions

According to the DWD grid data, the study period was warmer than the long-term (10.8 and 10.9°C for year 1 and year 2 vs. 9.95°C). Both years were drier than long term (682 and 681 vs. 817 mm) but late 2017 was still wetter than normal (256 vs. 215 mm, October to December). The summers of 2018 and 2019 were characterized by extreme heat and prolonged droughts leading to temperature anomalies of 0.74 and

Table 2. Input data for the radiative forcing models: Average CO₂-C (including harvest C), CH₄ and N₂O emissions of the 2-year field trial, assigned IPCC land use class for each plot and corresponding emission factors (IPCC 2014) all in g m⁻² a⁻¹, and C export by TSR in kg/m². Please note that IPCC emission factors include fluvial C exports and emissions from ditches.

| Approach | Average GHG Emissions (Field Trial) | IPCC Emission Factors | C Export TSR Topsoil-C kg/m² |
|----------|-------------------------------------|-----------------------|-----------------------------|
|          | CO₂-C g m⁻² a⁻¹ | CH₄-C g m⁻² a⁻¹ | N₂O-N g m⁻² a⁻¹ | Assigned IPCC Land Use Class | CO₂-C g m⁻² a⁻¹ | CH₄-C g m⁻² a⁻¹ | N₂O-N g m⁻² a⁻¹ | “Deep-drained Nutrient-rich Grassland” |
| IG       | 1,582 ± 48.1     | 13.4 ± 13.6          | 0.4 ± 0.2                  | 641                        | 5.6                  | 0.82              | 0              |
| OS       | 412.4 ± 18.9     | 69.7 ± 17.1          | 0.2 ± 0.2                  | 74                         | 22.4                 | 0                 | 0              |
| OS + mow.| 778.9 ± 37.6     | 107.8 ± 50           | 0.3 ± 0.5                  | “Rewetted Rich”            | 1                   | 10.0              | 0              | 17.49 |
| TSR30    | −26.9 ± 11.9     | 3.2 ± 0.3            | −0.1 ± 0.5                 | “Rewetted Poor”            | 30.6                 | 0.5               | 0.3            | 20.10 |
| TSR30 + Sphag. | −80.5 ± 11.4 | 2.6 ± 0.4            | −0.1 ± 0.2                 |                             | 0                   | 0                 | 37.05          |
| TSR60    | 30.6 ± 8.2       | 0.5 ± 0.1            | 0 ± 0.3                    |                             | 123.6                | 1.1               | 0.2            | 38.87 |
Table 3. Greenhouse gas emissions (in g/m²) of the status quo plot (“IG”) and the six restoration approaches in year 1 (24 September 2017 to 25 September 2018) and year 2 (25 September 2018 to 25 September 2019) and C export by TSR.

| Approach     | Year   | CO₂-C g/m² | Harvest-C g/m² | CH₄-C g/m² | N₂O-N g/m² | Topsoil-C kg/m² |
|--------------|--------|------------|----------------|------------|------------|-----------------|
| IG           | Year 1 | 185.1 ± 16.4 | 445.5 ± 18.7 | 27 ± 13.6 | 0.3 ± 0.1 | 0               |
|              | OS     | 123 ± 11.4  | 0              | 90.8 ± 16.6 | 0.2 ± 0.1 | 0               |
|              | OS+mow | 406.9 ± 13.9 | 300.6 ± 15.6 | 111.8 ± 36.2 | 0.1 ± 0.2 | 0               |
| TSR30        |        | −39.3 ± 5.8  | 0              | 2.5 ± 0.3  | −0.1 ± 0.1 | 17.49 ± 0.95    |
| TSR30 + Sphag.|       | −76.8 ± 5.5  | 0              | 2.1 ± 0.3  | −0.1 ± 0.1 | 20.10 ± 1.17    |
| TSR60        |        | 35.1 ± 3.6   | 0              | 0.3 ± 0.1  | 0 ± 0.2    | 37.05 ± 1.57    |
| TSR60 + Sphag.|      | −154.5 ± 4.8 | 0              | 1 ± 0.1    | −0.1 ± 0.1 | 38.87 ± 3.21    |
| IG           | Year 2 | 1892.8 ± 33  | 640.6 ± 24.5   | −0.1 ± 0.1 | 0.4 ± 0.2  | 0               |
|              | OS     | 701.8 ± 15   | 0              | 48.5 ± 4   | 0.2 ± 0.1  | 0               |
|              | OS+mow | 631.8 ± 17.9 | 218.6 ± 25.6   | 103.8 ± 34.4 | 0.6 ± 0.5 | 0               |
| TSR30        |        | −14.5 ± 10.3 | 0              | 3.9 ± 0.1  | −0.2 ± 0.4 | 0               |
| TSR30 + Sphag.|       | −84.2 ± 10   | 0              | 3.1 ± 0.3  | 0 ± 0.2    | 0               |
| TSR60        |        | 26 ± 7.4     | 0              | 0.7 ± 0.1  | 0 ± 0.2    | 0               |
| TSR60 + Sphag.|      | −92.7 ± 8.9  | 0              | 1.2 ± 0.2  | 0 ± 0.1    | 0               |

Figure 2. Radiative forcing (RF) of the status quo (intensive grassland, “IG”) and the six restoration approaches for different topsoil decomposition scenarios. The rewetting approaches either retained their original surface (“OS”) or were subjected to topsoil removal of approximately 30 cm (“TSR30”) or approximately 60 cm depth (“TSR60”), Sphagnum introduction (“+Sphagnum”), or mowing (“+mowing”). For the topsoil removal approaches, the removed carbon was assumed to be either released immediately in the first year after rewetting (“ts_immediate,” IPCC 2006), or at annual decomposition of 25%, 10%, 5%, and 1% (e.g. “ts_1perc,” Cleary et al. 2005). “noacc” shows the radiative forcing without accounting for the removed topsoil. The released carbon was assumed to be entirely converted to carbon dioxide. Shaded areas represent the combined errors of the on-site emissions. Insets show whole range of instantaneous radiative forcing whereas big plots are zoomed in to allow for better visibility of differences between TSR plots.
Figure 3. Radiative forcing (RF) of emission factors (Table 2, IPCC 2014) in combination with climatic effects of topsoil removal (TSR) from the field experiment for different topsoil decomposition scenarios. Keeping the status quo (intensive grassland, “IG”) is compared to three restoration approaches, which either retained their original surface (“OS”) or were subjected to TSR of approximately 30 cm (“TSR30”) or approximately 60 cm depth (“TSR60”). The restoration approaches with additional measures (Sphagnum introduction or mowing) are not shown because the emission factors for these approaches would be the same as their regular counterparts (Table 2). For the TSR approaches, the removed C was assumed to be either released immediately in the first year of restoration (“ts_immediate,” IPCC 2006), or at annual decomposition of 25%, 10%, 5%, and 1% (e.g. “ts_1perc,” Cleary et al. 2005). “Noacc” shows the radiative forcing without accounting for the removed topsoil, wherefore the RF of TSR30 and TSR60 is the same. The released C was assumed to be entirely converted to carbon dioxide. Shaded errors represent an uncertainty of 10% for the emission factors.

Field GHG Measurements

Overall, magnitude and variation of measured fluxes were highest in IG and the OS plots (Figs. S3–S5). In year 1, CO₂ emissions were highest from IG and OS+mowing (Table 3). Rewetting alone (OS) reduced CO₂ emissions by approximately 80% compared to IG. The TSR plots were close to CO₂-neutral, with the highest uptakes found in the plots with additional Sphagnum introduction (TSR30 + Sphagnum and TSR60 + Sphagnum). CH₄ emissions were highest in the OS plots and close to zero in the TSR plots. N₂O emissions were generally close to zero, with a tendency of emissions in the IG and OS plots and of uptake in the TSR plots.

In year 2, CO₂ emissions from IG and OS substantially increased, but the relative reduction by rewetting alone remained
similar (approximately 70%). CH₄ emissions in OS were almost 50% lower compared to year 1 whereas they remained similar in OS+ mowing. In the TSR plots, CH₄ emissions slightly increased. N₂O emissions remained the same in year 2.

Radiative Forcing
Compared to IG, OS and OS+ mowing had reduced climate warming after approximately 40 and approximately 158 years (Fig. 2). All restoration approaches with TSR rapidly had reduced climate warming than IG. For “ts_immediate,” the compensation points were reached after approximately 6 years and approximately 13 years (TSR30 and TSR60 approaches), after which the restoration approaches were less climate warming than IG. At a decomposition of 25 and 10%, the compensation points were reached after approximately 6–0 years for the TSR30 and after approximately 14–11 years for the TSR60 approaches. At a decomposition of 5% or lower, all TSR plots were less climate warming than IG from the first year after rewetting (Fig. 2). At the current C uptake by TSR30 + Sphagnum and TSR60 + Sphagnum, these approaches had switched the bog from net warming to net cooling after approximately 171–175 and approximately 209–211 years.

When using IPCC emission factors for the on-site emissions, the overall magnitude of climate warming was lower even for IG (Fig. 3). In contrast to the field-trial GHG emissions, rewetting without TSR immediately had reduced climate warming than IG. At a decomposition of 100 to 5%, compensation points compared to IG were reached after approximately 22–13 years for the TSR30 and after approximately 40 years for the TSR60 approaches. At a decomposition of 1%, the TSR30 and TSR60 approaches immediately had reduced climate warming than IG. Rewetting without TSR had increased climate warming than the TSR approaches after less than 40 years (TSR30) and 165 years (TSR60) for all topsoil decomposition scenarios (Fig. 3). Based on IPCC emission factors, no approach had switched from net warming to net cooling.

Discussion
Rewetting
CO₂ emissions of IG were, on average, approximately twice as high as the IPCC emission factors for the same peatland category (IPCC 2014), probably reflecting a combination of intensive management and the extreme summer heat of 2018 and 2019. Even though CO₂ emissions were substantially reduced by rewetting alone (70–80%), they remained high in our field experiment. In addition, very high CH₄ emissions occurred due to partial inundation of the surface depressions in the OS plots, which are on the upper end of the range of emission factors for this peatland category (IPCC 2014). Inundated nutrient- and biomass-rich, degraded topsoil is by far the single-largest contributor to high CH₄ emissions after rewetting of agriculturally used bogs (Huth et al. 2020). Although rare, the combination of high CO₂ and CH₄ emissions also occurred in an inundated nutrient-rich temperate fen peatland that was previously under intensive grassland use (Hahn-Schöffl et al. 2011; Franz et al. 2016). In such cases, rewetting at the original surface becomes less climate warming than IG only after decades posing a major challenge for restoration after long-term drainage and agricultural land use. However, maintaining high water levels and partial inundation during summer heat likely amplified CH₄ emissions in our trial. Because large-scale year-round supply of nutrient-poor water will not be possible in practical raised bog restoration, water has to be retained during the winter months by dams compensating for a summer deficit when water tables will naturally drop which likely reduces CH₄ emissions caused by rewetting at the original surface. Based on many field studies, rewetting at the original surface is therefore immediately less climate warming than drainage-based agricultural use (Günther et al. 2020).

Topsoil Removal
In the first years after restoration, TSR plots were CO₂ sinks except for TSR60, which has remained mostly bare peat throughout the study period (Rosinski et al. 2021). CH₄ emissions were lower than from peatlands in the same category (IPCC 2014), but a reestablishment of the vegetation and the associated microbial communities could increase CH₄ emissions in the long term (Putkinnen et al. 2018). N₂O emissions were close to zero with a tendency of small uptake in the TSR plots, which could indicate an N₂O consumption potential due to anoxic substrate-poor conditions as found in weakly disturbed fen mires (Buchan et al. 2019).

When assuming that all C export by TSR is emitted as CO₂ in the first year (IPCC 2006), TSR is more climate warming than IG and rewetting at the original surface for a few years. Cleary et al. (2005) argue that, depending on the use after extraction, an annual decomposition of 1–10% is more realistic. Under the assumption that our field-trial emissions will persist over time, a decomposition of less than 10% is immediately less climate warming than IG and rewetting at the original surface. Because there is no substantial difference in GHG emissions between TSR30 and TSR60 plots, a shallow TSR is always less climate warming than a deeper one, as long as nutrient-poor and acidic conditions for successful bog restoration are provided (Rosinski et al. 2021).

Based on IPCC emission factors, rewetting at the original surface is the best option in the short term, except for very low decomposition of the removed topsoil of 1%, where slightly higher CO₂ and CH₄ emissions from nutrient-rich restored peatlands outweigh the CO₂ emissions from topsoil decomposition. However, after a few decades, additional CO₂ emissions also from faster decomposing topsoil become less climate warming. TSR prior rewetting thus benefits the climate because it reduces sustained CO₂ emissions and removes CH₄ hot spots (i.e. inundated depressions).

Sphagnum Introduction
In our study, the development of a Sphagnum carpet leads to a substantial C uptake probably amplified by year-round water supply. Since Nugent et al. (2018) find a similarly high C uptake
of approximately 78 g m\(^{-2}\) a\(^{-1}\) in an extracted bog 14 years after restoration with moss transfer, sustained high uptake rates are also possible on larger spatial scales without a controlled water management. This means that restored bogs could become net cooling in the long term despite C export through TSR. Therefore, TSR prior rewetting benefits the climate because it provides nutrient-poor and acidic conditions for rapid \textit{Sphagnum} establishment resulting in an on-site cooling effect. We thus recommend as much TSR prior rewetting as needed to enable these conditions.

Acknowledgments

This study was funded by the Federal Agency of Nature Conservation (BiN, grant number: 3516892003) with resources from the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and by the European Regional Development Fund (ERDF) distributed through the NBank (grant number: 85008462). AG, GJ, and FK gratefully acknowledge funding by the European Social Fund (ESF) and the Ministry of Education, Science and Culture of Mecklenburg-Vorpommern within the scope of the project WETSCAPES (grant number ESF/14-BM-A55-0030/16). CG gratefully acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—GRK 2000/1. The authors declare no conflict of interest.

Open Access funding enabled and organized by Projekt DEAL.

LITERATURE CITED

Andersen R, Farrell C, Graf M, Muller F, Calvar E, Frankard P, Caporn S, Anderson P (2017) An overview of the progress and challenges of peatland restoration in Western Europe. Restoration Ecology 25:271–282

Bivand R, Rundel C (2017) rgeos: Interface to Geometry Engine - Open Source (‘GEOEs’). R package

Bröns K, Verhoeven JTA, Hefting MM (2014) Short period of oxygenation releases latch on peat decomposition. Science of the Total Environment 461:61–68

Buchen C, Roobroeck D, Augustin J, Behrendt U, Boeckx P, Ulrich A (2019) High N2O consumption potential of weakly disturbed fen mires with dis-similar denitrifier community structure. Soil Biology and Biochemistry 130:63–72.

Cleary J, Roulet NT, Moore TR (2005) Greenhouse gas emissions from Canadian Buchen C, Roobroeck D, Augustin J, Behrendt U, Boeckx P, Ulrich A (2019) Short period of oxygenation releases latch on peat decomposition. Science of the Total Environment 461:61–68.

Franz D, Koebsch F, Larmounou E, Augustin J, Sachs T (2016) High net CO2 and methane turnover and the associated microbial communities in restored cut-over peatlands is strongly linked with increasing Sphagnum abundance. Soil Biology and Biochemistry 116:110–119

Quinty F, LeBlanc M-C, Rochefort L (2020) Peatland restoration guide – planning restoration projects. PERG, CSPMA and APTHQ, Quebec

Renou-Wilson F, Wilson D, Rigney C, Byrne K, Farrel C, Müller C (2018) Network monitoring rewetted and restored peatlands/organic soils for climate and biodiversity benefits (NEROS) EPA Research Report No. 236, Environmental Protection Agency, Wexford, Ireland

Rosinski E, Bartel A, Günther A, Heinz S, Hofer B, Jurasinski G, Schötz H-P, Ulrich K, Huth V (2021) Wiederherstellung von Hochmoorbiotopen nach intensiver Grünlandnutzung – Drei Jahre Vegetationsentwicklung im Feldversuch OptiMoor. Natur und Landschaft 96:192–201

Tiemeyer B, Albiac Borraz E, Augustin J, Bechtold M, Beetsz S, Beyer C, et al. (2016) High emissions of greenhouse gases from grasslands on peat and other organic soils. Global Change Biology 22:4134–4149

Verhoeven JTA (2014) Wetlands in Europe: perspectives for restoration of a lost paradise. Ecological Engineering 66:6–9

Wickham H (2009) ggplot2: elegant graphics for data analysis. Springer, Dordrecht, New York

Wilson D, Alm J, Laine J, Byrne K A, Farrell EP, Tuittila E-S (2009) Rewetting of cutaway peatlands: are we re-creating hot spots of methane emissions? Restoration Ecology 17:796–806

Supporting Information

The following information may be found in the online version of this article:
Table S1. Average water tables (mean ± 1 SD) manually measured in dip wells close to the GHG measurement collars in each plot during the 2-year study period (19 September 2017 to 24 September 2019).

Figure S1. Soil temperatures in °C measured in approximately 5 cm depth during CO₂ flux measurements over the 2-year study period (24 September 2017 to 25 September 2019).

Figure S2. Development of Sphagnum moss height in TSR30 + Sphagnum and TSR60 + Sphagnum during the 2-year study period (24 September 2017 to 25 September 2019) in relation to initial peat surface.

Figure S3. Measured CO₂ fluxes in mg m⁻² h⁻¹ during the 2-year study period (24 September 2017 to 25 September 2019).

Figure S4. Measured CH₄ fluxes in mg m⁻² h⁻¹ during the 2-year study period (24 September 2017 to 25 September 2019).

Figure S5. Measured N₂O fluxes in mg m⁻² h⁻¹ during the 2-year study period (24 September 2017 to 25 September 2019).