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RESEARCH ARTICLE

Climate change mitigation potential of restoration of boreal peatlands drained for forestry can be adjusted by site selection and restoration measures

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Peatland restoration is seen as a key nature-based solution to tackle climate change and biodiversity loss. In Europe, nearly 50% of peatlands have been drained during the last decades, which have shifted their soils to carbon dioxide (CO_2) sources. Soils of forestry-drained peatlands are known to vary from CO_2 sources to small sinks depending on their fertility and wetness. When peatlands are restored, it can be expected that rates of CO_2 and methane exchange will vary depending on site fertility and wetness. We generated seven restoration pathways with different starting and end points and assessed the climate impacts of them. The GHG emission coefficients were compiled from literature, and radiative forcing was calculated for a 500-year time period since restoration. All seven restoration pathways improved carbon sink capacity; however, the climate impact differed from cooling to warming. The highest cooling impact occurred in a pathway leading from nutrient-rich drained peatlands toward tree-covered spruce or pine mires. Warming impacts occurred in a pathway leading from nutrient-poor drained peatlands toward open peatlands. The results of this study can be used to help identify peatland sites and restoration targets to maximize climate change mitigation from restoration. In practice, however, restoration has to fulfill other targets, such as biodiversity safeguarding, improvement of hydrological conditions, and socio-economic aspects. Fulfilling all targets simultaneously requires compromises on all targets.

Key words: carbon storage, climate change mitigation, forestry drainage, GHG emission, peatland, rewetting

Implications for Practice

- As carbon dioxide and methane emissions in forestry-drained and restored peatlands vary based on site conditions (fertility, water table level, and vegetation type), the selection of restoration sites and measures influences the climate mitigation potential of restoration.
- Climate change mitigation potential is at its greatest when nutrient-rich forestry-drained peatlands are restored toward tree-covered spruce or pine mires where the water level is below the peat surface.
- Climate change mitigation potential is smallest when nutrient-poor drained peatlands are restored toward open peatlands where water level is near the peat surface.
- The results of this study can be used to identify potential peatland restoration sites to maximize their climate change mitigation.

Introduction

Peatlands store around 30%, or 644 Gt of the planet's terrestrially available carbon (Yu et al. 2010). As the carbon storage capacity is strongly dependent on land use, particularly drainage state, the role of peatland management in climate change mitigation is important (UN Environment 2019; UN Decade on Ecosystem Restoration 2020–2030; Convention on Biological Diversity 2021; Lehtonen et al. 2021). Globally, 12% and in Europe, nearly 50% of peatlands have been drained and degraded (UNEP 2022). Rewetting of peatlands is seen as a potential means to mitigate climate change, as it efficiently

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slows down peat decomposition (Leifeld & Menichetti 2018; Humpenöder et al. 2020). Yet, the restoration techniques (Zak & McInnes 2022) and the initial state of the drained site (Ojanen & Minkkinen 2020) may strongly impact the rate of mitigation. For example, in boreal forestry-drained peatlands, carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions are relatively low when compared to agriculturally used peatlands or peatlands located in warmer climate, and typically the drained peatlands emit low amounts of methane (CH_4), except from ditches that typically cover a small proportion of the land (Ojanen & Minkkinen 2020; Rissanen et al. 2023).

In Finland, the main objective of restoration of forestry-drained peatlands has been to restore the structure and function of the peatland ecosystem by improving the quality of species' habitats and biotopes, fulfilling the goals of ecological restoration (Aapala & Similä 2014). In practice, this means filling in or blocking the ditches and managing tree cover so that it resembles the native reference system. Restoration experiments in boreal forestry-drained peatlands show promising results in recovering vegetation. In most cases, the peat-forming vegetation, namely *Sphagnum* mosses, dwarf shrubs, and sedges, recovers within 5–10 years because many of these generalist species remain in drained peatlands in small quantities even decades after drainage (e.g. Laine et al. 2011; Hedberg et al. 2012; Haapalehto et al. 2017). The reestablishment of the more demanding species of inundated or forested habitats or specific nutrient conditions (rich fen species) has been more difficult (Mälson et al. 2010; Hedberg et al. 2012; Maanavilja et al. 2014).

The studies in which greenhouse gases have been measured from restored boreal forestry-drained peatlands show that CO_2 and CH_4 exchange returns to a similar range as in undrained peatlands (e.g. Urbanová et al. 2013; Laine et al. 2019; Purre et al. 2019). However, the rate of green house gas (GHG) emissions and restoration mitigation potential varies between drained peatland types (Ojanen & Minkkinen 2020). Some of the boreal nutrient-poor forestry-drained peatlands have quite low soil CO_2 and N_2O emissions (Ojanen et al. 2013; Minkkinen et al. 2020; Alm et al. 2023), while the growing trees are binding CO_2 more efficiently than the low-stature vegetation of pristine peatlands if the harvest of trees is not considered. In addition, due to the low water table level, the CH_4 emissions are small except for the ditches (Ojanen et al. 2010; Rissanen et al. 2023). As long as the tree stand is alive and not harvested, the climate impact of forestry drainage in such habitats is mostly cooling (Ojanen et al. 2013). Restoring such a site likely increases CH_4 emissions and removes the carbon sink formed by the trees (Wilson et al. 2016; Ojanen & Minkkinen 2020), limiting the climate impact of the restoration of nutrient-poor drained peatlands. Nutrient-rich sites, on the other hand, have considerable soil CO_2 and N_2O emissions (Minkkinen et al. 2020; Alm et al. 2023) and thus have more potential for climate change mitigation by restoration (Ojanen & Minkkinen 2020).

As is the case with boreal forestry drained peatlands, the CO_2 and CH_4 gas exchange of restored peatlands also varies. It may be expected that the variability is similar as between undrained peatland types. Generally, in an average year, undrained peatlands take up and store CO_2 from the atmosphere (e.g. Lund et al. 2010). There are some differences in the long-term C accumulation between peatland types with nutrient-poor types offering more stable accumulation (Turunen et al. 2002). The CH_4 emissions tend to vary more between peatland types so that increasing wetness, nutrient availability, and in case of the boreal peatlands, the amount of aerenchymous plants all cause higher emissions (Turetsky et al. 2014; Zhang et al. 2021). More simply, the open wet sedge-dominated fens tend to have much higher CH_4 emissions than the drier *Sphagnum* and shrub-dominated bogs and the drier pine and spruce mires (Turetsky et al. 2014; Zhang et al. 2021; Table S2).

In addition to the above-mentioned differences in GHG exchange between boreal peatland types, the radiative effects and the atmospheric lifetimes of CO_2, CH_4, and N_2O differ, all together affecting the climate impact of different peatland types over time. Due to the lifetime differences between the gas species, the time frame chosen for inspecting the climate change mitigation potential of restoration is crucial. The shorter the time frame, the greater the impact the increased CH_4 emissions have compared to reduced CO_2 emissions. Therefore, if the aim of restoration is climate change mitigation, the type of peatlands to be restored (starting point for restoration) and the end point of restoration, that is, whether restoration aims at wet open peatland habitat or drier habitat that remains covered by trees after restoration, affect the effectiveness of the restoration. The largest climate benefits may be achieved by restoring those drained habitats that produce the highest emissions in their drained state, or alternatively, by steering restoration toward habitats that produce lower CH_4 emissions. So to say, the key to maximize the climate benefits of peatland restoration is to maximize the difference in climate effects between the status quo trajectory and the restoration trajectory. Previously, the climate mitigation potential has been evaluated based on a rather coarse division of peatlands into nutrient-rich and poor types, without a focus on the restoration end point (Wilson et al. 2016; Ojanen & Minkkinen 2020).

The aim of this study was to evaluate the climate change mitigation potential of the restoration of boreal forestry-drained peatlands. We asked how much we could manage the climate impact of restoration by selecting nutrient-rich or nutrient-poor peatland sites to be restored and by choosing different restoration end points (open and tree-covered). All restoration end points considered here are natural peatland habitats in Finland, namely fens, bogs, pine mires, and spruce mires. These native references are analogous to Gann et al. (2019), yet they may not fully represent the historical reference, that is, the peatland type existing before drainage. We generated seven restoration pathways and assessed the climate impacts of each. The study was limited to boreal Finland, where more than half of the original 10 Mha of peatlands have been drained for forestry (Turunen & Valpola 2020). In addition to biodiversity losses, peatland drainage has impacted water quality, caused peat degradation, and CO_2 emissions. It is estimated that drainage has decreased the carbon storage of Finnish peatlands by 0.17–0.51 Gt C (Turunen & Valpola 2020).

We compiled published estimates for soil CO_2, CH_4, and N_2O emission coefficients for forestry-drained and undrained boreal peatland types from Finland and nearby boreal areas. As the available data from restored peatlands does not yet allow for metanalysis but indicates that gas exchange is similar to undrained peatlands (e.g. Wilson et al. 2016), we use the undrained peatland data for restored peatlands. To incorporate the radiative effects and atmospheric lifetimes of the three greenhouse gases, we used the REFUGE 4 tool (Lindroos 2023) to calculate the radiative forcing for a 500-year time period since restoration. REFUGE model results show the time dynamics that different restoration pathways (nutrient-rich or nutrient-poor peatlands, restoration toward treeless or tree-covered state) have on the global radiative forcing. We discuss the climate impact results relative to habitat biodiversity value.

Methods

Restoration of Peatlands in Finland

Nearly all peatland restoration in Finland has been carried out on forestry-drained peatlands in nature conservation areas. The main objective has been to restore the structure and function of the native peatland ecosystem by improving the quality of species' habitats and biotopes, fulfilling the goals of ecological restoration (Aapala & Similä 2014). The first peatland restoration experiments were performed in the 1970s and 1980s to protect exceptionally valuable species and habitats, while the launch of EU Life funding in the 1990s marked the beginning of large-scale restoration using heavy machinery and accompanied by monitoring and scientific research (Fig. 1; Aapala & Similä 2014). Currently, the restored peatland area exceeds 55,000 ha (Fig. 1, Metsähallitus 2023, personal communication) with a growing share also in private lands.

Peatland Site Types and Restoration Pathways

To estimate the impact of restoration on GHG exchange, the first step is to pair the restoration starting points, that is, the forestry-drained peatland site types, with the potential native restoration end points, that is, the type of peatland that the restoration practices aim for. Here, we use peatland site type classification for the pairing. In the case of forestry-drained peatlands, this is a prominent tool, as the drained sites often still carry some characteristics and plant species from the time before drainage. The Finnish peatland site type classification is based on vegetation communities and habitat wetness, and the forestry-drained types have been paired with undrained natural peatland types with similar nutrient status (Laine et al. 2018). In this study, we expect that with restoration, it is possible to create habitats similar to undrained natural peatland site types (Table S1) and use them as potential restoration objectives (Laine et al. 2018).

While in Finnish tradition, the forestry-drained peatlands are divided into 5–10 categories based on the nutrient and moisture status (Laine et al. 2018), in this paper, we follow Wilson et al. (2016) by using two categories: nutrient poor and nutrient rich. The literature estimates on soil GHG emissions support this division to be efficient, while there is currently not enough knowledge to support further division (Ojanen et al. 2010; Ojanen & Minkkinen 2019; Minkkinen et al. 2020).

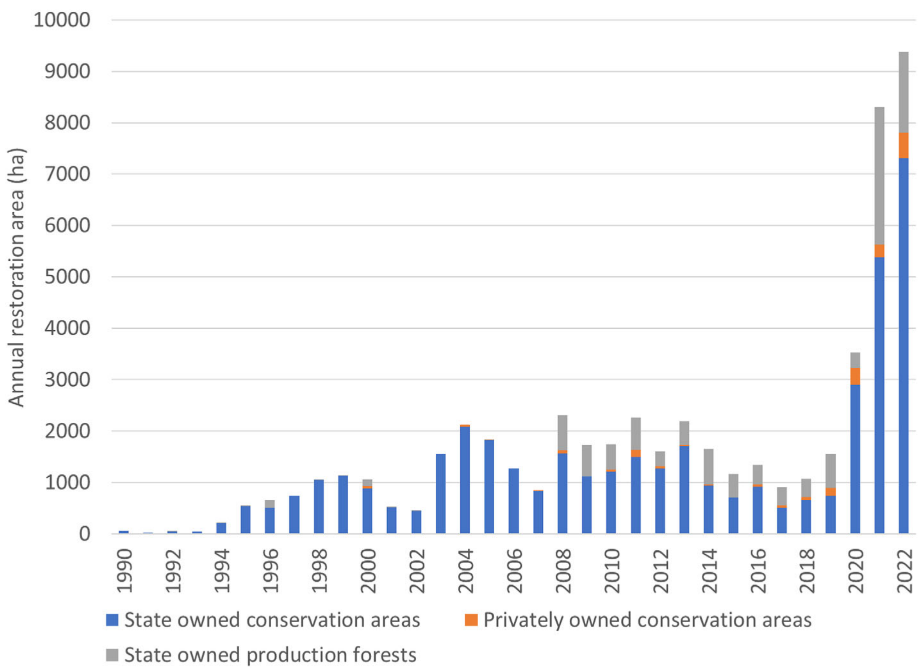

Figure 1. Annual peatland restoration area (ha) in Finland carried out by Metsähallitus, the managing body of the state-owned lands responsible for most of the peatland restoration executed in Finland.

The restoration outcomes are defined based on native undrained peatland site types (Laine et al. 2018) that are pooled into five categories (tree-covered spruce mires, tree-covered pine mires, open eutrophic or mesotrophic fens, open oligotrophic fens, and open ombrotrophic bogs) based on nutrient status and wetness. The division is based on nutrient status and wetness-driven differences in CH_4 emissions. The defined restoration pathways are shown in Figure 2.

In the pairing of drained peatland habitats and native references, the emphasis is on the similar nutrient status of the site, while wetness can be modified by the restoration practices. As the two drained and five undrained categories include several gradually displacing site types, more than one potential restoration pathway is possible (Fig. 2). As an example, in the nutrient-rich drained category of habitats, tree species range from broadleaved trees to Norwegian spruce and Scots pine, while the nutrient status ranges from eutrophic to the high end of oligotrophic. The nutrient-poor drained peatlands quite solely grow Scots pine and are weakly oligotrophic to ombrotrophic.

Soil GHG Emission Estimates for Different Peatland Types

To evaluate the climate impacts of different restoration pathways (Fig. 2), GHG emission estimates (g gas m^{-2} a^{-1}) for each peatland category, namely the two forestry-drained and five restoration outcomes (Fig. 2) were derived from the literature as follows.

For the two nutrient status classes of forestry-drained peatlands, we obtained soil CO_2, CH_4, and N_2O emission rates from Finnish studies targeting the different forestry-drained peatland site types. N_2O emissions are from Minkkinen et al. (2020). CH_4 soil emissions are from Ojanen et al. (2010), but emissions from ditches (2.5% of the area) come from Rissanen et al. (2023). Soil CO_2 emissions are derived from Ojanen and Minkkinen (2019). CO_2 emission estimates are complemented by adding the amount of C that has arrived as deposition and not through plant photosynthesis (2.5 g C m^{-2} a^{-1}) (Lindroos et al. 2007), while for C leaving the peatland as dissolved organic carbon (DOC) emission (10.5 g C m^{-2} a^{-1}) (Sallantaus 1994) 90% is expected to be emitted into atmosphere as CO_2 (Evans et al. 2014; Hiraishi et al. 2014), while 10% is stored in other ecosystems.

For the GHG emission estimates of restoration outcomes, we made the assumption that the gas fluxes at restored sites will be similar to those at undrained peatlands and that the effect of rewetting on the emissions of CO_2, CH_4, and N_2O will be immediate and constant for 500 years. These assumptions were made because only a few short-term studies on gas fluxes from restored forestry-drained peatlands are available (Komulainen et al. 1998, 1999; Juottonen et al. 2012; Urbanová et al. 2013; Koskinen et al. 2016; Laine et al. 2019; Purre et al. 2019). In addition, Wilson et al. (2016) showed that the average rates after rewetting are close to those of undrained peatlands.

To derive CO_2 estimates for the five different undrained peatland classes (Table S1; Fig. 2), we used long-term average C accumulation rates measured from Finnish peatlands (Turunen et al. 2002). This study by Turunen et al. (2002) is the only one spanning all major peatland types and with replicated sites. In addition, using the long-term accumulation rates decreases the impact of varying weather conditions for CO_2 exchange. The long-term C accumulation was converted into CO_2 following Equation (1).

$$CO_2\text{exchange} = \begin{array}{l}(\text{C accumulation} + 0.1 \times \text{DOC emission} \\ + \quad CH_4\text{-C emission} \quad - \text{C} \\ \text{deposition}) \times 3{,}664 [\text{g } CO_2/\text{g C}]\end{array} \quad (1)$$

For C that has arrived as deposition and not through plant photosynthesis, we used a value 0.5 g C m^{-2} a^{-1} (Lindroos et al. 2007). Of the DOC-emission (9.5 g C m^{-2} a^{-1}; Sallantaus 1994) 90% is expected to be emitted to the atmosphere as CO_2 (Evans et al. 2014, Hiraishi et al. 2014), while 10% is stored in other ecosystems. The part of accumulated carbon that is emitted as CH_4 is specific for each peatland type (see below).

For CH_4 emission estimates, we carried out a literature survey looking for all published values from Finland and the nearby boreal region (Table S2). We searched for studies from which, in addition to seasonal or annual CH_4 emission it was possible to conclude the peatland site type. In the case of seasonal values (usually given for the period May to September), we estimated the winter emission to be 15% of the seasonal emission, similar to Saarnio et al. (2007).

Climate Impact Calculations

The climate impact of restoration for each restoration pathway (Fig. 1) was calculated (1) as the change (from drained to restored state emissions) in carbon balance in the atmosphere (including change in CO_2 and CH_4 fluxes, measured as C), (2) as the change in total emissions (CO_2 equivalent emissions including the change in CO_2, CH_4, and N_2O in 100- and 500-year time frame), and (3) by using the REFUGE 4 tool to estimate the additional radiative forcing for a 500-year time period since restoration.

REFUGE 4 tool calculates time-dynamic impacts of user-given emission scenarios. It follows the Intergovernmental Panel on Climate Change (IPCC)1 AR6 methodology, covers CO_2, CH_4, and N_2O, and can handle both positive and negative emissions of these gases. The tool was developed in 1993 by Korhonen et al. (1993) and updated in 2000s (Monni et al. 2003) and 2010s (Pingoud et al. 2012). The fourth version, REFUGE 4, has been published as an open access tool, including documentation and validation (Lindroos 2023).

REFUGE 4 calculates the change in the atmospheric concentration of gases. Peatland restoration creates an impact on atmospheric carbon balance and consequently changes the carbon fluxes to land and ocean sinks. REFUGE calculates these behaviors and illustrates them in result figures. REFUGE 4 results show

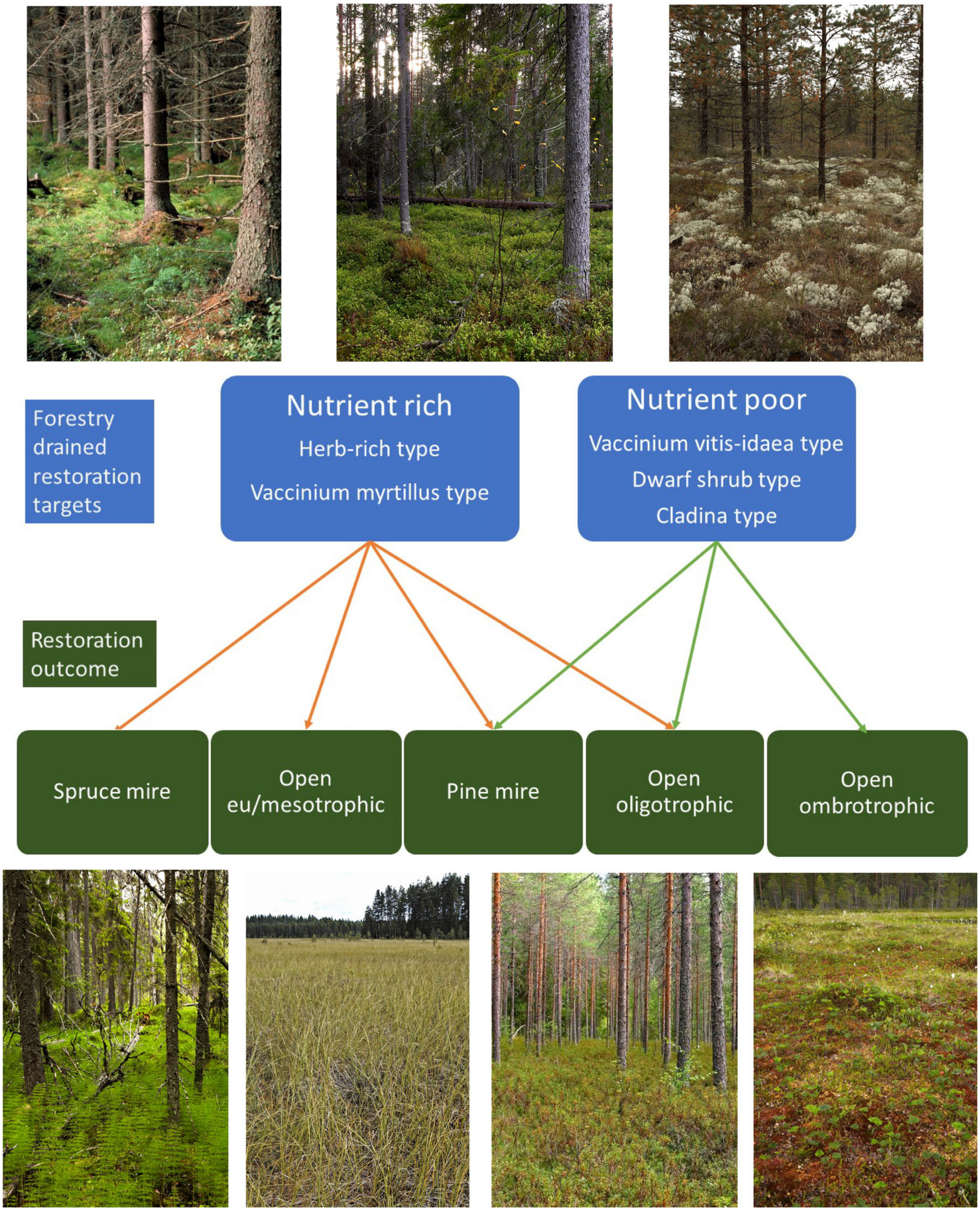

Figure 2. Potential restoration pathways. Restoration is targeted for forestry-drained peatlands that are divided into two classes based on their nutrient status. Peatland vegetation is dependent on ecohydrology, namely quantity and quality of water; therefore, with restoration practices (by affecting the amount and quality of water directed to the restoration site), it is possible to guide their development toward forested or open peatland habitats and in some cases, even impact the nutrient availability. In addition, the habitats within the two drainage groups vary, and some habitats at the poorer end of the nutrient-rich group (those that before drainage were wet open peatlands) grow pine and have nutrient imbalances due to which it may be more feasible to direct their development toward pine mire or oligotrophic fen. For these reasons several restoration outcomes are suggested for nutrient rich and poor sites. Drained peatland site types of photos in the upper row from left to right: *Vaccinium myrtillus* type, *V. vitis-idaea* type, and *Cladonia* type; natural peatland sites types in the lower row from left to right: Spruce mire, Tall sedge fen, Dwarf shrub pine bog, and *Sphagnum fuscum* pine bog. Photos by J. Laine.

Table 1. Estimates of CO_2, CH_4, and N_2O emissions with ±SE (g gas m^{-2} a^{-1}) and global warming potential (GWP) for a time horizon of 100 and 500 years (GWP100 of $CO_2 = 1$, of $CH_4 = 29.8$ and of $N_2O = 273$ CO_2–equivalents, GWP500 of $CO_2 = 1$, of $CH_4 = 10$ and of $N_2O = 130$ CO_2-equivalents; IPCC 2021, AR6 WG1 Ch7 Table 7.15) for forestry-drained and restored (undrained) peatlands. Negative values indicate removal from atmosphere. The impact of restoration on atmosphere's C balance (CO_2 and CH_4, g C gas m^{-2} a^{-1}) is calculated as the difference between drained and restored peatlands. The change in CO_2-equivalent emissions describes how much restoration impacts the overall GHG emission balance. The standard error estimates were calculated by summing the component standard error estimates with conventional variance summing methods.

Forestry drained					*Restored*					*Change*	
Site type	*CO_2*	*CH_4*	*N_2O*	*100/500 years CO_2-eq*	*Site type*	*CO_2*	*CH_4*	*N_2O*	*CO_2-eq 100/500 years*	*in C balance*	*in 100/500 years CO_2-eq*
Nutrient rich	265 (±70)	0.34 (±0.12)	0.23 (±0.04)	338 (±71)/ 298 (±70)	Spruce mire	−91 (±6)	1.7 (±0.4)	0.1 (±0.01)	−13 (±14)/ −61 (±7)	−96 (±21)	−351 (±105)/ −359 (±88)
					Open eu/ meso	−104 (±6.5)	15 (±2.3)	0.1 (±0.01)	370 (±69)/ −59 (±24)	−90 (±23)	+32 (±162)/ −239 (±107)
					Pine mire	−97 (±8.2)	4.8 (±3.1)	0.03 (±0.003)	54 (±93)/ −45 (±32)	−95 (±24)	−284 (±186)/ −343 (±116)
					Open oligo	−124 (±7.3)	22 (±2.6)	0.03 (±0.003)	540 (±78)/ −100 (±21)	−90 (±13)	+202 (±170)/ −198 (±110)
Nutrient poor	−45 (±30)	0.34 (±0.12)	0.08 (±0.004)	−14 (±30)/ −32 (±30)	Open oligo	−124 (±7.3)	22 (±2.6)	0.03 (±0.003)	540 (±60)/ −100 (±21)	−5 (±13)	+554 (±141) / +131 (±72)
					Open ombro	−95 (±8.9)	9.7 (±1.6)	0.03 (±0.003)	202 (±49)/ −5.9 (±18)	−7 (±12)	+216 (±112)/ −38 (±64)
					Pine mire	−97 (±8.2)	4.8 (±0.8)	0.03 (±0.003)	54 (±25)/ −45 (±11)	−11 (±12)	+68 (±88)/ −13 (±55)

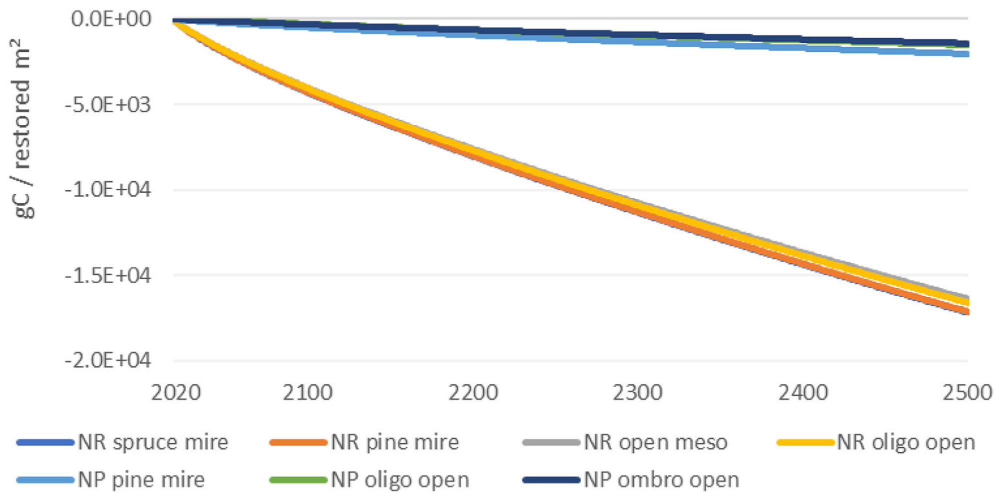

Figure 3. Impact on the atmosphere's C content (g C/restored m^2) of the seven restoration pathways (NP, nutrient poor; NR, nutrient rich).

time dynamics arising both from the warming effect of different gases and possible variations by years in emission scenarios.

Absolute Global Forcing Potential (AGFP) results describe the warming effect of the emission scenarios. The AGFP results are in watts per square meter for the surface of Earth and are typically studied as annual values and time-integrated values. Time-integrated results are very similar to global warming potential (GWP)-methodology which studies time-integrated AGFP of pulse emissions and compares them to the impact of CO_2 pulse. As the unit of AGFP (W m^2) is quite unintuitive, REFUGE aims to concretize this by converting time-integrated AGFP into more regularly used units, $MtCO_2$-eq. The conversion is done by comparing results to a constant annual 1 Mt CO_2 emission scenario. A more detailed description of the AGFP and conversion to constant annual CO_2 emissions are in the REFUGE documentation (Lindroos 2023).

Here, we calculate estimates for politically important emission reduction target years 2035 and 2050 (16- and 31-year horizons). Finland aims to be carbon neutral by 2035 (Finnish Climate Act 423/2022), and the EU has a carbon neutrality target for 2050 (European Climate Law 2021/1119). In addition, we calculate results with 100- and 500-year time horizons, where 100/500-year time-integrated results can be compared to GWP 100/500 results (Table 1).

Results

Carbon and Greenhouse Gas Balance

Restored peatlands are larger CO_2 sinks and have quite variable CH_4 emissions and negligible N_2O emissions. The CH_4 emissions depend on wetness and vegetation type, being highest at the wet sedge fens (open oligotrophic). Restoration improves the atmosphere's C balance (i.e. makes it more negative by increasing the soil C sink) in most restoration pathways (Table 1). Yet, due to the high CO_2 emissions of forestry-drained nutrient-rich class, their restoration has a stronger

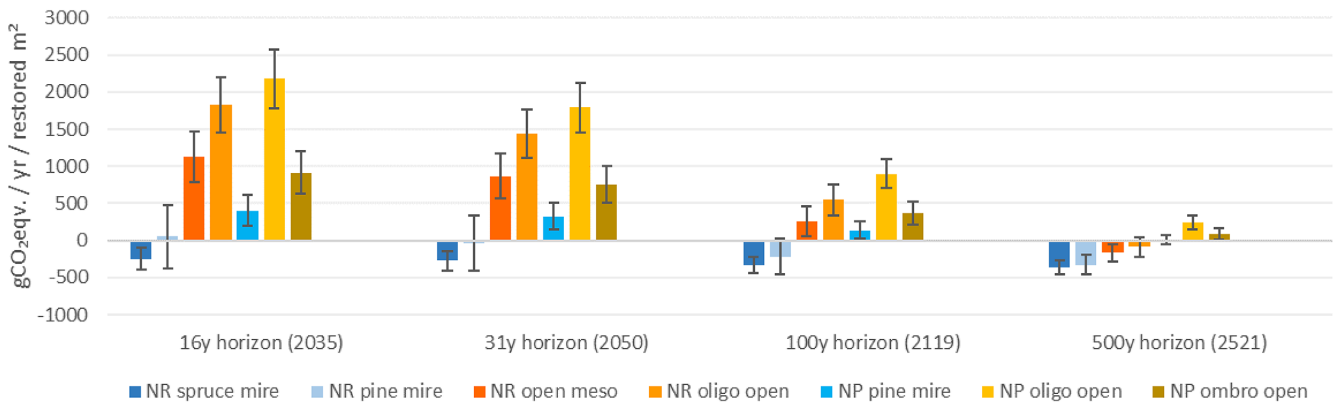

Figure 4. Constant annual CO_2-eq emission ± SE of different restoration pathways starting from nutrient rich forestry-drained peat soils (NR) or nutrient poor forestry-drained peat soils (NP). The tree stand CO_2 sink is not included in the calculations. Constant annual CO_2-eq emission is calculated from reference emission scenarios that have constant annual CO_2 emissions of x tCO_2/year and the same warming effect with a given time horizon. It is a time-dynamic version of static CO_2-eq emissions calculated with, e.g. GWP100 factors.

impact on C balance compared to the restoration of nutrient-poor peatlands.

Impacts on the atmosphere's carbon balance are smaller when taking into account changes in the carbon land and ocean sinks and impacts on processes in the atmosphere (Fig. 3). After 100 years, the amount of C in the atmosphere is approximately 45% lower when calculated with REFUGE (Fig. 3) compared to simplified calculations (Table 1) due to land and ocean sinks absorbing carbon from the atmosphere.

CO_2-Equivalent Emissions

When summing emissions with GWP100 factors, most restoration pathways increase the total GHG emissions; however, the uncertainty of the estimates is large due to relatively large uncertainties in all components of GHG emissions (Table 1). With GWP100 factors, high CH_4 emissions from restored peatlands have a much larger impact on total CO_2-equivalent emissions than the reduced CO_2 emissions. The restoration pathways that improved the emission balance calculated at the 100-year time frame were nutrient-rich drained peatlands restored toward tree-covered peatland types, that is, spruce mires and pine mires. For nutrient-poor drained peatlands, restoration pathway aiming at pine mire slightly increases emissions when summed with GWP100 factors (Table 1). When considering a longer time frame of 500 years, only the restoration pathway from nutrient-poor drained peatland to open oligotrophic fen leads to increased CO_2-equivalent emissions.

The more detailed calculations of emission dynamics by REFUGE show that the warming impact of nutrient-rich forestry-drained peatlands restored toward spruce mires would correspond to the warming impact of an emission scenario that has constant annual emission reduction of 250 g CO_2-eq for each square meter of restored land in the 16-year horizon and 330 g CO_2-eq m^{-2} a^{-1} reduction in the 100-year horizon; however, the uncertainties of the estimates are high (Fig. 4). All restoration pathways have a cooling impact when the time horizon increases due to the longer lifetime of CO_2 in the atmosphere than CH_4. However, restoration pathways that increase the amount of CH_4 emissions have a significantly higher warming effect with shorter time horizons (Table 1).

Radiative Forcing

Results from the REFUGE tool show the time dynamics that different restoration pathways have on the global radiative forcing (measured as AGFP). Positive impact means that the measure warms the planet, while negative values indicate cooling.

All four restoration pathways for nutrient-rich forestry-drained peatlands are more beneficial in long term than in the near term (Fig. 5). Spruce mire pathway has the lowest emissions and reduces the global radiative forcing from the beginning of the inspected time horizon. Open oligotrophic restoration pathway shows increasing annual radiative forcing up to 2080, and the cumulative impact on global warming is positive despite the small reduction toward the end of the 500-year horizon.

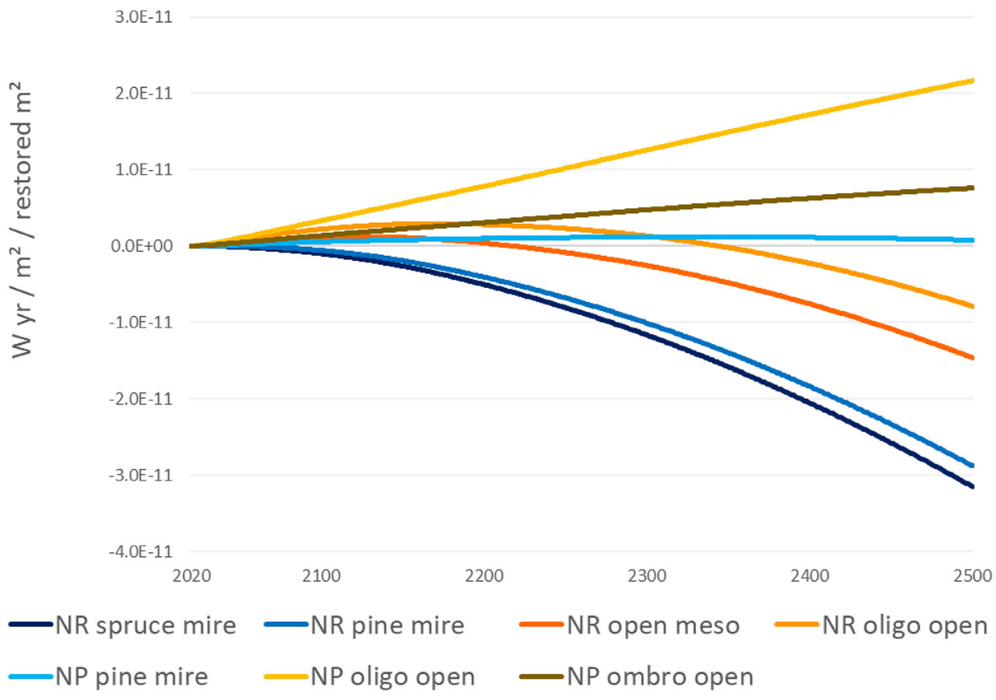

Figure 5. Time-integrated additional Absolute Global Forcing Potential (AGFP) caused by restoring forestry-drained peatlands to different types of peatland habitats (restoration outcomes) starting from nutrient rich (NR) forestry-drained peatland types and nutrient poor (NP) forestry-drained peatland types. m^2 refers to global m^2, not m^2 in the peatland. The impact is calculated for 1 m^2 of restored area. The tree stand CO_2 sink is not included in the calculations.

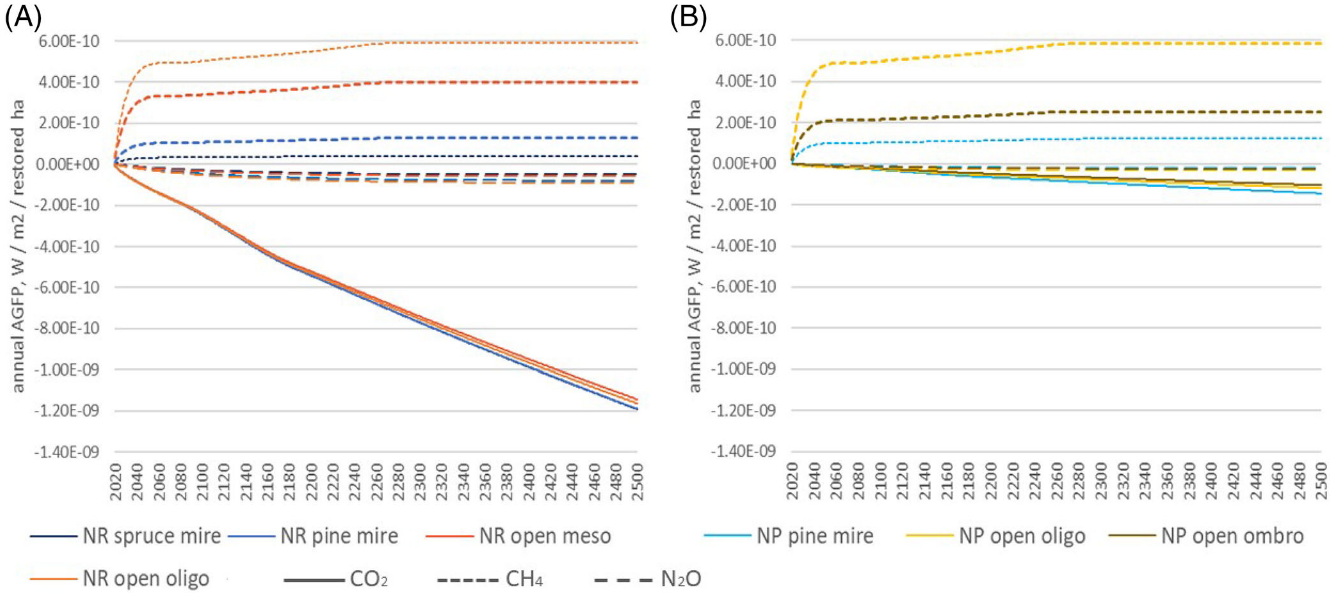

Figure 6. Annual impact of different restoration pathways on the AGFP by different greenhouse gases (A) nutrient-rich forestry-drained peatlands, (B) nutrient-poor forestry-drained peatlands. The overall impact of reduction pathways is calculated as an integral from 2020 to studied end point in Figure 5. m^{-2} refers to global m^{-2}, not m^{-2} in the peatland. The impact is calculated for 1 ha of restored area.

Restoration pathways of *nutrient-poor* forestry-drained peatlands have a significantly longer period of increasing AGFP than those for nutrient-rich peatlands (Fig. 5). The cumulative impact of all studied restoration pathways for nutrient-poor peatlands showed a warming impact over the studied 500-year horizon. The order of the restoration pathways was the same as in the case of nutrient-rich soils: the drier pine mire pathway had the lowest warming impact, while the open oligotrophic pathway led to the highest warming. Based on the radiative forcing dynamics, we formed three climate response groups: (1) from nutrient rich toward spruce and pine mires; (2) from nutrient rich toward open peatlands and from nutrient poor toward pine mire; and (3) from nutrient poor toward open oligotrophic or ombrotrophic peatlands.

The different GHG's, CO_2, CH_4, and N_2O have different impact on annual AGFP over time and depending on the restoration pathway (Fig. 6). The additional impact of reduced CO_2 emissions increases over time, while that of increased CH_4 emissions saturates after a first decades. The differences in AGFP between restoration of nutrient-rich and nutrient-poor forestry-drained peatlands is caused by the level of CO_2 emissions mitigated by restoration. The differences between the restoration outcomes, however, are caused by the rate of CH_4 emissions initiated by restoration, being clearly higher at open peatland types than at spruce or pine mires (Fig. 6).

Discussion

The results show that the climate impact of peatland restoration depends on the restoration pathway, that is, the site characteristics before restoration and the end point of restoration. Here, we focused on impacts based on changes in soil and underground vegetation GHG emissions and excluded the dynamic tree stand. Our results highlight that restoration of forestry-drained peatlands is not just one or two incidents (as the nutrient poor and nutrient rich categories in Wilson et al. 2016), but the choices of which types of peatlands to restore and toward which status in terms of tree cover and wetness are crucial if restoration is carried out to support climate change mitigation.

All seven restoration pathways have the potential to improve carbon storage and sink capacity, however, the climate impact of the pathways differs. We defined three climate response groups among the seven pathways. The first group, from nutrient rich toward tree-covered spruce and pine mires shows fast climate cooling impact soon after restoration. The second group, from nutrient rich toward open peatlands and from nutrient poor toward tree-covered pine mires, shows a warming impact after restoration due to increased CH_4 emissions. As time passes, however, the additional AGFP first saturates, and finally the impact turns to climate cooling. The third type, from nutrient poor toward open oligotrophic or ombrotrophic peatlands, shows increasing annual additional forcing after restoration that saturates but remains high for decades. The difference in climate impact between restoring nutrient-rich and poor drained peatlands is mostly down to the amount of CO_2 emissions that restoration mitigates, but when comparing the different restoration outcomes within the two groups, the differences in climate impact are caused by the rate of CH_4 emissions initiated by restoration.

When purely concentrating on climate benefits, the best restoration option would be to restore nutrient-rich drained peatlands (that have high soil CO_2 emissions) toward tree-covered spruce mires. Pristine spruce mires have low CH_4 emissions (Nilsson et al. 2001; Huttunen et al. 2003;

Table 2. Impact of different restoration pathways starting from nutrient-rich (NR) or nutrient-poor (NP) forestry-drained peatlands on climate, biodiversity, and water quality; risk level for restoration measures to fail; availability of land for restoration depends on willingness of landowner to restore forestry-drained land. Green color indicates positive impact, low risk and high availability, red color is the opposite.

Restoration pathway	*Climate change mitigation potential*	*Biodiversity*	*Water quality*	*Risk level for failure in restoration measures*	*Availability for restoration*
NR → spruce mire					
NR → pine mire					
NR → open mire					
NP → pine mire					
NP → open mire					

Minkkinen et al. 2007), which makes the potential climate cooling impact immediate. In Finland, such spruce mires are among the most threatened peatland types, with high conservation value (Kontula & Raunio 2019), and therefore, this restoration pathway would have high benefits for biodiversity. As a downside, restoration of drained spruce-dominated peatlands is challenging due to their complicated hydrology. Despite intensive planning and skilled operations, failures may occur. If restoration fails, there is a risk for very high CH_4 emission and water pollution (Koskinen et al. 2016, 2017). When restoration is conducted outside conservation areas and on private land, also socio-economic constraints need to be considered (Andersen et al. 2017; Zak & McInnes 2022). Private landowners likely have little interest to restore such highly productive, drained peatlands. More so, even the forestry-drained spruce sites are relatively rare compared to other peatland types in Finland (Korhonen et al. 2021) and therefore if concentrated on this pathway, the restoration area in any case would remain quite modest.

Climate-wise the second-best option is to restore the nutrient-rich pine-dominated drained peatlands toward tree-covered pine mires, again a pathway leading to high CO_2 emission mitigation and low CH_4 emissions (Nykänen et al. 1998; Minkkinen et al. 2007). In practice, this restoration pathway demands minimal effort, as only partial tree removal and ditch infilling are needed. Restoration of such site would have long-term benefits for water quality (Menberu et al. 2017). However, pine mires are among the most typical peatland types in Finland, and therefore restoring them do not offer great biodiversity wins in terms of rare habitats or species (Kontula & Raunio 2019). While the area of drained pine-dominated peatlands would offer large areas for restoration, the landowners may be reluctant to restore such sites as they typically support productive tree stands.

Climate-wise, fewer gains are received when restoring nutrient-poor forestry-drained peatlands. Such sites are likely the most available ones for restoration in Finland, as drainage has led to approximately 0.8 milj. ha (Laiho et al. 2016) of low-productive forest stands. As the value of these for landowner is low, they are likely more willing to offer such sites for restoration. While large climate or biodiversity gains are not achieved by restoration, it does have long-term benefits for water quality (Menberu et al. 2017).

Climate-wise, the worst pathway is to restore the nutrient poor drained sites toward wet, sedge-dominated peatlands. Pristine sedge fens have higher CH_4 emissions than other peatland site types (Zhang et al. 2021), and the same can be expected for restored habitats with similar characteristics. Such habitats, however, have high biodiversity value in Finland and offer habitat for most of the peatland obligate red list species (Hyvärinen et al. 2019). In addition, restoration has benefits for water quality (Menberu et al. 2017).

Our results give insight into the potential restoration pathways for climate change mitigation. In practice, restoration has to fulfill many simultaneous objectives and support the provision of several ecosystem services (Table 2). The most widely recognized ecosystem services provided by peatlands are climate regulation, biodiversity and habitat provision, and water flow and quality regulation (Kimmel & Mander 2010). As drainage is the most significant factor in the decline in the provision of these services, restoration is paramount to improve the status of peatlands (e.g. Humpenöder et al. 2020). Nevertheless, socio-economic aspects and public acceptance must also be taken into account. It is not realistic to restore only certain types of peatlands with certain type of management practices. Although the restoration of nutrient-rich forestry-drained peatlands would have the greatest potential for climate change mitigation, these peatlands also have high forestry potential. Thus, a variety of needs have to be reconciled when planning the management of peatlands (Table 2).

Limitations of the Study Approach

This study is based on published literature estimates of soil GHG emission of drained peatland site types. The estimates are based on data from several study sites, yet the gas exchange likely varies from year to year according to weather conditions. We also did not account for the tree growth C sink and storage that decreases to some extent when forestry-drained peatlands are restored. The dynamic and unstable C sink of trees is also strongly affected by management practices. It may also be argued that increasing albedo due to removal of trees may counterbalance the decreasing tree C sink (Lohila et al. 2010); however, more studies on the subject are needed.

In addition, the GHG estimates for restored peatlands were taken from literature-based values of pristine peatland types toward which they are expected to develop. After restoration, the peatland vegetation undergoes succession and correspondingly, the gas exchange likely changes over the years. Unfortunately, there are no long-term studies on gas exchange at restoration sites, and even long-term monitoring of vegetation is limited to a few sites and years. Therefore, we are currently unable to include successional changes in gas fluxes following restoration in this study.

All GHG estimates for the forestry-drained and restored site types have relatively high uncertainties, making the uncertainty of the estimated climate impacts (i.e. CO_2-eq emissions in different time frames) high. More uncertainty in the estimates is caused by the ongoing climate change; gas exchange of both drained and pristine/restored peatlands is likely to change. Increasing CO_2 emissions are projected for drained peatlands due to higher temperatures (Alm et al. 2023). There is evidence that global warming has already increased the peat decomposition rate, DOC and CO_2 emissions in boreal-drained peatlands (McCarter et al. 2021). It may be expected that with ongoing climate change, the decomposition will further increase in the future. The response of pristine and restored peatland to increasing temperature and drier conditions seems less straight-forward. While decomposition will likely increase, in some habitats net CO_2 uptake may increase due to vegetation change-derived increased productivity (Laine et al. 2019; Köster et al. 2023). Therefore, projecting climate impacts to the unsure future is complicated. One crucial impact of climate change is the increased risk of forest fires (Davies et al. 2013; Wilkinson et al. 2023). A fire in drained peat soil may release large amounts of carbon stored in peat soil and trees, and it may expand to large areas as peat fires are difficult to stop. Rewetting prevents/slows down peat decomposition and prevents forest fires, as wet peat is significantly less inflammable than dry peat (McCarter et al. 2021).

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Undrained peatland site types included in the five restoration outcome classes.

Table S2. Data used for calculating methane emissions of restored (i.e. pristine) peatland site type groups.

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