Rewetting Offers Rapid Climate Benefits for Tropical and Agricultural Peatlands But Not for Forestry-Drained Peatlands

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Abstract Peat soils drained for agriculture and forestry are important sources of carbon dioxide and nitrous oxide. Rewetting effectively reduces these emissions. However, rewetting also increases methane emissions from the soil and, on forestry-drained peatlands, decreases the carbon storage of trees. To analyze the effect of peatland rewetting on the climate, we built radiative forcing scenarios for tropical peat soils, temperate and boreal agricultural peat soils, and temperate and boreal forestry-drained peat soils. The effect of tree and wood product carbon storage in boreal forestry-drained peatlands was also estimated as a case study for Finland. Rewetting of tropical peat soils resulted in immediate cooling. In temperate and boreal agricultural peat soils, the warming effect of methane emissions offsets a major part of the cooling for the first decades after rewetting. In temperate and boreal forestry-drained peat soils, the effect of rewetting was mostly warming for the first decades. In addition, the decrease in tree and wood product carbon storage further delayed the onset of the cooling effect for decades. Global rewetting resulted in increasing climate cooling, reaching $-70$ mW (m$^2$ Earth)$^{-1}$ in 100 years. Tropical peat soils (9.6 million ha) accounted for approximately two thirds and temperate and boreal agricultural peat soils (13.0 million ha) for one third of the cooling. Forestry-drained peat soils (10.6 million ha) had a negligible effect. We conclude that peatland rewetting is beneficial and important for mitigating climate change, but abandoning tree stands may instead be the best option concerning forestry-drained peatlands.

1. Introduction

Efficient climate change mitigation requires a drastic decrease in greenhouse gas emissions during the next few decades (Intergovernmental Panel on Climate Change [IPCC], 2018). Strengthening greenhouse gas sinks in ecosystems is needed in addition to emissions reductions from industry, energy production, and transport (Rockström et al., 2017; Rogelj et al., 2018). Strengthening ecosystem sinks could mean, for example, increasing the carbon sink in forests or decreasing land use-induced carbon loss from soils.

Peatlands are important regulators of atmospheric greenhouse gas concentrations and the climate. Undrained peatlands are, on the one hand, carbon dioxide (CO$_2$) sinks due to peat accumulation (e.g., Loisel et al., 2014; Yu, 2011). On the other hand, they are methane (CH$_4$) sources due to favorable methanogenesis conditions (e.g., Couwenberg et al., 2010; Korhola et al., 2010; Pangala et al., 2013). These two greenhouse gases have very different properties (Etminan et al., 2016; Myhre et al., 2013a, 2013b): CH$_4$ has a 137-fold radiative efficiency (including indirect effects) per kilogram gas than CO$_2$ when in the atmosphere. However, CH$_4$ is also very short lived (atmospheric lifetime 12 years) compared to CO$_2$.

Due to CH$_4$ emissions, an undrained peatland may have a climate-warming effect (a positive radiative forcing) for up to several thousands of years since its initiation (Figure 1; Frolking et al., 2006; Frolking & Roulet, 2007; Mathijssen et al., 2014, 2017). Undrained peatland will eventually have a climate-cooling effect. The warming effect of the short-lived CH$_4$ stabilizes over time, and increasing CO$_2$ levels are removed from the atmosphere due to peat accumulation.

Peatlands drained for agriculture or forestry have a completely different effect on the climate compared to undrained peatlands. As drainage decreases methanogenesis and favors methanotrophy due to a lowered water table, drained peatlands are negligible CH$_4$ sources or even act as CH$_4$ sinks (e.g., Couwenberg et al., 2010; Hiraishi et al., 2014b; Ojanen et al., 2010). On the other hand, drainage causes peat loss due to enhanced aerobic decomposition. Peat loss leads to CO$_2$ and nitrous oxide (N$_2$O) emissions, as
carbon (C) and nitrogen are released from peat (e.g., Hiraishi et al., 2014b; Tiemeyer et al., 2016). Peatland drainage may initially have a climate-cooling effect due to the decrease in CH_4 emissions but will eventually have a climate-warming effect due to the persistent CO_2 and N_2O emissions caused by progressive peat loss (Figure 1; Dommain et al., 2018; Laine et al., 1996).

If a drained peatland is rewetted, greenhouse gas exchange levels close to those of undrained peatland may be reinstated, as the CO_2 and N_2O emissions decrease and the CH_4 emission increases (Wilson et al., 2016). Based on emission factors for drained and rewetted peatlands, converted to CO_2 equivalents by applying global warming potentials, rewetting has been found to have a climate-cooling effect over various climate and land use categories (Hiraishi et al., 2014b; Wilson et al., 2016). Thus, peatland rewetting has been promoted as a way to effectively mitigate climate change (Joosten et al., 2012). However, the CO_2 equivalent approach has two loopholes that prevent us from making well-founded conclusions on the potential that peatland rewetting offers in mitigating current climate change:

1. Global warming potentials used to calculate the CO_2 equivalents are accurate only when comparing pulse emissions (= emissions that occur at this moment; Myhre et al., 2013a, 2013b). When comparing sustained emissions due to permanent land use changes, global warming potentials underestimate the relative importance of short-lived greenhouse gases—that is, CH_4, in the case of peatlands.

2. Even if specific sustained global warming potentials (e.g., Neubauer & Megonical, 2015) are used instead, the resulting CO_2 equivalents describe the average effect on the climate over a certain time frame, typically exceeding 100 years. However, both warming and cooling effects may occur during the chosen time frame (Figure 1).

To reveal the temporal dynamics of rewetting on the climate, radiative forcing needs to be considered instead of CO_2 equivalents. As the effect of rewetting on the climate mirrors that of drainage, it can have both warming and cooling phases (Figure 1). If compared to that of peatland initiation, the effect of rewetting is different: In addition to causing an undrained-like CH_4 source and CO_2 sink, successful rewetting halts the CO_2 and N_2O emissions from drained peat soil. Thus, a much faster climate-cooling effect can be expected for rewetting than for peatland initiation (Figure 1).

So far, only ground vegetation and soil have been considered when compiling the emission factors for drained and rewetted peatlands (Hiraishi et al., 2014b; Wilson et al., 2016). This omission of tree stands may be all encompassing for agricultural peatlands rewetted to open fens but is insufficient in many other cases. Changes in tree stand C dynamics due to rewetting may have both (1) climate-warming and (2) climate-cooling effects.

(1) For example, increasing tree biomass is a large CO_2 sink in boreal forestry-drained peatlands (e.g., Hommeltenberg et al., 2014; Lohila et al., 2010; Minkkinen et al., 2018; Uri et al., 2017). As drainage has largely increased average tree growth and biomass (e.g., Hökkä et al., 2008; Seppälä, 1969), rewetting is likely to largely decrease tree growth and the CO_2 sink of the tree biomass. This decrease has a climate-warming effect. (2) Many undrained peatlands are forested such as...
the tropical peat swamp forests of Indonesia (Page et al., 1999). Rewetting a peatland drained and cleared for agriculture back into an undrained forest (Lampela et al., 2017) creates a growing tree stand and a CO₂ sink to the tree biomass. This CO₂ sink has a climate-cooling effect. These tree stand effects should be considered when evaluating the climate change mitigation potential of peatland rewetting.

This study aims to answer two questions: Can the rewetting of peatlands drained for agriculture and forestry be used to mitigate climate change? How important would the rewetting be on a global scale? For this purpose, we constructed radiative forcing scenarios for rewetting peat soils belonging to different climate and land use categories by applying soil emission factors. These emission factors vary greatly between the categories, and thus, the simulations offer a tool for inspecting the effect of rewetting on a wide range of soil and climatic conditions. Combining the radiative forcing scenarios with a global area estimate of drained peatlands, we further calculated a radiative forcing scenario for rewetting all these drained peat soils. In addition, we analyzed the importance of trees in boreal forestry-drained peatlands by building scenarios for tree biomass and wood product C storages for drained and rewetted cases in Finland.

2. Materials and Methods

2.1. Effect of Rewetting on Soil Net Emissions

To estimate the effect of peatland rewetting on climate, we created 100-year scenarios for CO₂, CH₄, and N₂O net emissions from the soil due to rewetting. When a peatland is rewetted, the greenhouse gas emissions of a drained peatland are replaced by those of a rewetted peatland. Thus, the effect of rewetting on the emissions of each gas is:

\[
\text{Effect of rewetting} = \text{net emission at rewetted peatland} - \text{net emission at drained peatland} \tag{1}
\]

In this study, the effect of rewetting was assumed to be instantaneous and thereafter constant. Emissions of CO₂, CH₄, and N₂O for different climate and land use categories based on the IPCC Wetlands Supplement (Hiraishi et al., 2014b) revised by Wilson et al. (2016) were applied (Table 1). On-site net gas emissions (net exchange of gas between the soil and ground vegetation and the atmosphere) were included. Methane emissions from the ditches of drained peatlands were also included (Hiraishi et al., 2014b; Wilson et al., 2016).

### Table 1

*Soil Emission Factors (t ha⁻¹ year⁻¹ of gas) for CO₂, CH₄, and N₂O at Drained and Rewetted Peatlands and the Effect of rewetting (= rewetted – drained) According to Wilson et al. (2016)*

| Zone      | Land use | Drained    | Rewetted   | Effect    |
|-----------|----------|------------|------------|-----------|
|           |          | CO₂        | CH₄        | N₂O       | CO₂        | CH₄        | N₂O       | CO₂        | CH₄        | N₂O       |
| Boreal    | cropland | 29.41      | 0.058      | 0.0204    | -1.64      | 0.17       | 0.0001    | -31.05     | 0.11       | -0.0203   |
| Boreal    | grassland| 21.34      | 0.060      | 0.0149    | -1.64      | 0.17       | 0.0001    | -22.98     | 0.11       | -0.0148   |
| Boreal    | forest NP| 1.36       | 0.012      | 0.0003    | -1.23      | 0.06       | 0.0001    | -2.59      | 0.04       | -0.0002   |
| Boreal    | forest NR| 3.85       | 0.007      | 0.0050    | -1.64      | 0.17       | 0.0001    | -5.49      | 0.16       | -0.0049   |
| Temperate | cropland | 30.11      | 0.058      | 0.0204    | 1.84       | 0.31       | 0.0001    | -28.27     | 0.26       | -0.0203   |
| Temperate | grassland NP| 20.57    | 0.060      | 0.0067    | -0.34      | 0.12       | 0.0001    | -20.91     | 0.06       | -0.0066   |
| Temperate | grassland NR DD| 23.51   | 0.074      | 0.0129    | 1.84       | 0.31       | 0.0001    | -21.67     | 0.24       | -0.0128   |
| Temperate | grassland NR SD| 14.34   | 0.064      | 0.0025    | 1.84       | 0.31       | 0.0001    | -12.50     | 0.25       | -0.0024   |
| Temperate | forest NP| 10.67      | 0.008      | 0.0044    | -0.34      | 0.12       | 0.0001    | -11.01     | 0.11       | -0.0043   |
| Temperate | forest NR| 10.67      | 0.008      | 0.0044    | 1.84       | 0.31       | 0.0001    | -8.83      | 0.31       | -0.0043   |
| Tropical  | cropland | 54.34      | 0.052      | 0.0079    | 1.89       | 0.08       | 0.0015    | -52.45     | 0.03       | -0.0064   |
| Tropical  | plantation| 58.01     | 0.046      | 0.0019    | 1.89       | 0.08       | 0.0015    | -56.12     | 0.04       | -0.0040   |

*Note. The emissions for CH₄ and N₂O are on-site emissions, including CH₄ emissions from ditches in drained peatlands. For CO₂, 90% of the dissolved carbon export is also included in addition to the on-site emission. Forest = forestry-drained, NP = nutrient-poor, NR = nutrient-rich, DD = deep drainage, SD = shallow drainage.*
The CO₂ emission also included 90% of the dissolved carbon export (Wilson et al., 2016), as this share has been estimated to end up in the atmosphere as CO₂ (Evans et al., 2015; Hiraishi et al., 2014b).

Three land use categories for drained peatlands were applied (Table 1) in the boreal and temperate zones, following the IPCC guidelines (Hiraishi et al., 2014b) and Wilson et al. (2016): cropland, grassland, and forestland. These categories were further divided into nutrient-poor and nutrient-rich subcategories and in the temperate zone further into deep and shallow drained subcategories, as the emission factors differ distinctly. The IPCC guidelines (Hiraishi et al., 2014b) and Wilson et al. (2016) divide drained and rewetted peat soils in the tropics into cropland and plantation (Table 1). There, cropland means the cultivation of short-rotation plants, whereas plantation typically comprises the cultivation of longer-rotation palm species and acacia trees. The emission factors of these land use categories are, however, very similar (Table 1).

High CH₄ emissions following rewetting have occasionally been observed (Koskinen et al., 2016; Vanselow-Algan et al., 2015), as, on the other hand, have very low emissions even years after rewetting (Juottonen et al., 2012; Komulainen et al., 1998). The emissions for rewetted peatlands applied in this study (Wilson et al., 2016) do not describe either of these situations. Rather, the applied emission factors that describe the average situation after rewetting are close to those of undrained peatlands (Wilson et al., 2016).

When calculating the effect on the climate of rewetting 1 ha of peatland, we simply assumed that the effect of rewetting on the emissions of CO₂, CH₄, and N₂O (Table 1) is constant for 100 years. However, when calculating the effect of rewetting all the 33 million ha of drained peatlands (Table 2), it would be unrealistic to assume that they could be rewetted at once. To be a bit more realistic, we assumed that they would be rewetted at a constant pace during the first 20 years (= 5% of the area is rewetted every year).

2.2. Area Estimates

Area estimates of peatlands drained for forestry and agriculture were searched for primarily in the National Inventory Submissions 2017 of the United Nations Framework Convention on Climate Change (Table 1). For up-to-date information, land use inventories, other publications, and local colleagues were also consulted when necessary. In many cases for forestry and virtually always for grassland, no division of the area into various emission factor subcategories was available. In such cases, an even distribution between subcategories was assumed for calculating the effect of global rewetting.

2.3. Contribution of Trees

Soil is not the only important stock of C in forestry-drained peatlands, as trees may also contain a considerable amount of C, which can change according to management. Thus, for this land use, that is, forestry-drained peatlands, we estimated the contribution of changes in tree biomass and wood product C storage to the effect of rewetting on greenhouse gas emissions. The estimation was carried out as a case study of forestry-drained peatlands in Finland because nearly half of the global forestry-drained area is situated in the country (Table 2) and because we had all the necessary data from Finland to calculate changes caused by various management scenarios. Emissions were calculated separately for nutrient-poor and nutrient-rich peatlands corresponding to the boreal nutrient-rich and nutrient-poor soil emission categories (Table 1). The effect of rewetting on soil net emissions was equivalent to the effects estimated in section 2.1.

The C sink/source potential of tree biomass and wood products varies greatly between possible management scenarios. Thus, four tree stand management scenarios were considered for tree biomass and wood product C storage at a regional scale, two for drained and two for rewetted peatlands. The purpose of these four scenarios was to describe the range of C storage by estimating minimum and maximum scenarios for drained and rewetted peatlands. Trees grow well on drained peatlands, enabling the accumulation of tree biomass. On the other hand, cuttings restrict tree biomass accumulation. Intensive forestry continues in the minimum scenario (1), with cuttings restricting tree biomass C storage. No cuttings occur in the maximum scenario (2), with all growth increasing tree biomass C storage. Further C storage increase in rewetted peatlands is prevented by decreased tree growth. In the maximum scenario (3), trees are not cut at rewetting, which maintains the current tree biomass C storage. In the minimum scenario (4), trees are cut at rewetting, leading to a drastic decrease in tree biomass C storage.
Scenario 1. Forest management continues (forestry): This scenario describes the development of tree biomass and wood product C storage under continuing forestry when applying a typical forest management scheme (rotation forestry, including thinnings, clear-cutting, and forest regeneration). At a regional scale, this scenario means that the stem volume increases until it reaches the rotation-mean stem volume. Cuttings increase the C storage in wood products.

Scenario 2. Forest management is discontinued and trees are abandoned (abandonment): This scenario describes the highest possible tree biomass in forestry-drained peatlands, meaning that the forest continues.
growing without cuttings until it reaches the maximum stem volume of an unmanaged stand (Minkkinen et al., 2001). On the other hand, wood product C storage decreases, as no new products are manufactured but the current products continue decaying.

Scenario 3. Peatland is rewetted by blocking ditches and trees are abandoned (abandonment and rewetting): This scenario describes the highest possible tree biomass in rewetted peatlands. Trees are not cut at rewetting, representing the restoration of a wooded mire. At a regional scale, current tree biomasses (Table 3) are much higher compared to undrained peatlands (Gustavsen & Päivänen, 1986; Heikurainen, 1971). Thus, the current biomass is the highest possible for rewetted peatlands. Wood product C storage decreases, as no new products are manufactured but the current products continue decaying.

Scenario 4. Peatland is rewetted by blocking ditches and trees are clear-cut (clear-cut and rewetting): This scenario describes the lowest possible tree biomass in rewetted peatlands. Trees are clear-cut at rewetting, representing the restoration of an open mire. Stems and canopies are harvested and merchantable stem parts are utilized for wood products and the rest is burned for energy (= C instantly released). Belowground biomass (stumps and roots) is left on the site and does not decompose due to rewetting (= current belowground biomass is sustained). Wood product C storage increases at first due to the clear-cut but subsequently decreases, as the current and new products decay.

Based on the management scenarios, four possible effects of rewetting on tree biomass and wood product C storage were calculated:

Effect of rewetting = C storage in clear – cut and rewetting scenario – C storage in forestry scenario (2)

Effect of rewetting = C storage in clear – cut and rewetting scenario – C storage in abandonment scenario (3)

| Site type | Initial volume m³ ha⁻¹ | Initial growth m³ ha⁻¹ year⁻¹ | Max volume m³ ha⁻¹ | Mean volume m³ ha⁻¹ | Area 1,000 ha | Share of pine |
|-----------|-------------------------|-------------------------------|-------------------|---------------------|---------------|---------------|
| **Southern Finland, Nutrient-Rich Sites** | | | | | | |
| Herb Rich | 150 | 8.1 | 774 | 217 | 391 | 0.23 |
| V. myrtillus | 150 | 7.1 | 729 | 149 | 646 | 0.49 |
| Low Productive* | 24 | 1.0 | 154 | 43 | 5 | 1.00 |
| Unproductive | – | – | – | – | – | – |
| **Southern Finland, Nutrient-Poor Sites** | | | | | | |
| V. vitis-idaea | 122 | 5.6 | 361 | 159 | 679 | 0.96 |
| Dwarf Shrub | 78 | 3.5 | 357 | 110 | 390 | 1.00 |
| Cladina* | 42 | 2.4 | 273 | 71 | 18 | 1.00 |
| Low Productive* | 24 | 1.0 | 154 | 43 | 102 | 1.00 |
| Unproductive | – | – | – | – | – | – |
| **Northern Finland, Nutrient-Rich Sites** | | | | | | |
| Herb Rich | 103 | 5.5 | 657 | 137 | 218 | 0.34 |
| V. myrtillus | 105 | 5.0 | 589 | 83 | 495 | 0.61 |
| Low Productive* | 22 | 0.2 | 78 | 24 | 41 | 0.97 |
| Unproductive | – | – | – | – | – | – |
| **Northern Finland, Nutrient-Poor Sites** | | | | | | |
| V. vitis-idaea | 79 | 3.9 | 382 | 103 | 901 | 0.97 |
| Dwarf Shrub | 56 | 2.6 | 316 | 84 | 330 | 1.00 |
| Cladina* | 39 | 1.4 | 190 | 51 | 2 | 1.00 |
| Low Productive* | 22 | 0.2 | 78 | 24 | 344 | 0.97 |
| Unproductive | – | – | – | – | – | – |

Note: Site types divide the area into productive forests (rotation-mean stem volume growth ≥ 1 m³ ha⁻¹ year⁻¹) of declining fertility (herb-rich > Vaccinium myrtillus > Vaccinium vitis-idaea > dwarf shrub > Cladina), low-productive forests (rotation-mean stem volume growth < 1 m³ ha⁻¹ year⁻¹), and unproductive, treeless areas. Sources: ¹Finnish National Forest Inventory for 2009–2013 (Korhonen et al., 2017; Antti Ihalainen/Natural Resources Institute Finland). ²Minkkinen et al. (2001).

Maximum and mean stem volumes not available in the original publication, estimated through linear regressions with initial growth.
Effect of rewetting = C storage in abandonment and rewetting scenario – C storage in forestry scenario

Effect of rewetting = C storage in abandonment and rewetting scenario – C storage in abandonment scenario

In addition, the effect of abandonment without rewetting was calculated for comparison:

Effect of abandonment = C storage in abandonment scenario – C storage in forestry scenario

Finally, the effect of rewetting (or abandonment) on C storage was converted to a 100-year scenario of CO₂ net emissions. The emission for year $n$ ($Emission(n)$) was calculated based on the effect on C storage at the end of the current (C storage($n$)) and previous (C storage($n-1$)) years as follows:

$$Emission(n) = C_{storage(n)} - C_{storage(n-1)}$$

The initial tree stem volumes and stem volume growths of all the management scenarios were based on the Finnish National Forest Inventory for 2009–2013 (Table 3). All the scenarios were calculated separately for each site type in southern and northern Finland (Table 3). Finally, area-weighted means were determined for nutrient-poor and nutrient-rich categories. Tree biomass total and aboveground and stem C storage were estimated by multiplying stem volume by the dominant species-specific biomass expansion factor (Table 4). Biomass and wood product C contents of 50% were assumed in all calculations.

In scenario 1, tree stem volume increased, asymptotically approaching the rotation-mean stem volume. The initial increment, corresponding to growth – cuttings, was estimated as follows: initial growth (Table 3) × the ratio of current mean increment and mean growth in Finland (Table 4), as information on the actual cuttings is not available separately for drained peatland forests. Wood product C storage was estimated as a constant ratio of wood product C storage/tree biomass C storage (Table 4).
In scenario 2, tree stem volume increased beginning with initial growth (Table 3), as there were no cuttings, asymptotically approaching the maximum stem volume of unmanaged stands (Table 3). The initial wood product C storage decayed exponentially, as defined by product-specific time constants (Table 4).

In scenario 3, initial tree biomass C storage remained unaffected throughout the study and wood product C storage decayed similarly to scenario 2. In scenario 4, we utilized the merchantable stem parts for wood products and the rest of the initial aboveground tree biomass C storage was instantly released to the atmosphere. Belowground initial C storage remained unaffected. After an initial increase, wood product C storage decayed similarly to scenario 2.

### 2.4. Radiative Forcing Calculations

First, scenarios for the atmospheric perturbation of CO₂, CH₄, and N₂O (= change in atmospheric gas levels) due to the emissions and removals (= negative emission) were calculated for the emission scenarios of rewetting. After entering the atmosphere, the gas levels reduced according to the exponential decay model with gas-specific lifetimes (Table 5). Carbon dioxide was divided into four fractions with different lifetimes describing the various processes removing CO₂ from the atmosphere at varying paces. For removals, the calculation of atmospheric perturbation was otherwise identical to that of emissions but the sign for perturbation was the opposite (− instead of +).

The radiative forcing (RF) scenario due to the perturbation scenario was calculated as follows: perturbation × radiative efficiency × indirect effects multiplier (Table 5). Radiative efficiency describes the direct effect of greenhouse gas on RF due to absorbing radiation and indirect effects describe the indirect effects due to changes in atmospheric chemistry caused by the greenhouse gas in question. Radiative efficiencies and indirect effects multipliers were assumed constant throughout the study, thus not considering the possible effects of climate change. The effect of the studied emissions and removals on the atmospheric concentration was also assumed negligible, thus not affecting the radiative efficiencies (Myhre et al., 2013a, 2013b).

The radiative forcing of CO₂ resulting from the atmospheric decay of CH₄ was taken into account by including it into the RF of CH₄ in the calculation. This effect of CH₄-derived CO₂ is demonstrated as a slow rise in the RF of constant CH₄ emissions after the rapid rise at the beginning (Figure 1a).

See, for example, Frolking et al. (2006) and Frolking and Roulet (2007) for detailed examples of calculating RF scenarios.

To compare the cooling (CO₂ and N₂O removals) and warming (CH₄ emissions, decrease in tree stand and wood product C storages) effects of rewetting, a warming/cooling ratio was calculated, describing the RF share (%) of the cooling effects offset by the RF of the warming effects:

$$\text{Warming/cooling ratio} = \frac{-[\text{RF (CH}_4 \text{)} + \text{RF (tree stand + wood product)}]}{[\text{RF (CO}_2 \text{)} + \text{RF (N}_2\text{O)}]} \times 100\%$$

### 3. Results

#### 3.1. Comparison of Land Use and Climate Categories

Different land use and climate categories showed distinctly different RF scenarios for rewetting peat soils (Figure 2). In the tropics, rewetting caused an immediate, almost linearly increasing climate cooling (negative RF) for both cropland and plantation soils. The net effect was cooling already at the beginning, as the increasing CH₄ emissions offset only a few percent of the cooling by decreasing the CO₂ and N₂O emissions.

The warming offset was much higher in temperate and boreal agricultural soils (Figure 2). Consequently, only boreal soils and temperate nutrient-poor grassland soils with their relatively low increases in CH₄
emissions experienced a cooling net effect at the beginning. Temperate nutrient-rich shallow drained grassland soil with its low decrease in CO₂ emissions and high increase in CH₄ emissions (Table 1) even showed a climate-warming effect during the first decades.

In forestry-drained soils, the temperate nutrient-poor case alone showed a climate-cooling effect within a few decades (Figure 2). For all the other cases, the increased CH₄ emissions offset over 100% of the cooling impact of decreased CO₂ and N₂O emissions for at least the first 40 years. Even 100 years after rewetting, the offset was at least 50%.

Figure 2. (left) Radiative forcing (RF) scenarios for rewetting 1 ha of drained peat soil in different land uses and climates. Right: The share (%) of the cooling effect (reduction of CO₂ and N₂O emissions) offset by the warming effect (increase in CH₄ emissions). Temp = temperate; bor = boreal; crop = cropland; grass = grassland; forest = forestry drained; NP = nutrient poor; NR = nutrient rich; SD = shallow drainage; and DD = deep drainage.
In addition to the temporal dynamics, the magnitude of the climate cooling also varied (Figure 2). In the tropics, an RF of \(-50 \times 10^{-10} \text{ W (m}^2 \text{ Earth})^{-1}\) for a hectare of peat soil was reached within 100 years. At temperate and boreal agricultural soils, typically half of that was reached. At temperate and boreal forestry-drained peatlands, the cooling was close to zero in most cases and approximately \(-8 \times 10^{-10} \text{ W (m}^2 \text{ Earth})^{-1}\) in the best case.

### 3.2. Global Rewetting of Peat Soils in 20 Years

Global rewetting of peat soils (without the effect of tree stands) resulted in increasing climate cooling, reaching \(-70 \text{ mW (m}^2 \text{ Earth})^{-1}\) in a century (Figure 3). Even though the area was nearly evenly distributed between tropical soils, temperate and boreal agricultural soils, and forestry-drained soils (Table 2), their

![Figure 3](image-url)  
*Figure 3. (left) The radiative forcing (RF) scenario for globally rewetting all the drained peat soils in 20 years. (right) The share (%) of the cooling effect (reduction of CO\(_2\) and N\(_2\)O emissions) offset by the warming effect (increase in CH\(_4\) emissions). Tropical = tropical croplands and plantations; agriculture = temperate and boreal croplands and grasslands; and forest = temperate and boreal forestry-drained peatlands.*

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![Figure 4](image-url)  
*Figure 4. Country-scale mean tree stand and wood product carbon storage (as CO\(_2\)) scenarios for different forest management scenarios for nutrient-poor and nutrient-rich forestry-drained peatlands in Finland. F = forestry; A = abandonment; CC + RW = clear-cut and rewetting; A + RW = abandonment and rewetting; and Init CO\(_2\) stor = carbon storage at year 0.*
shares in the climate cooling were uneven. The tropics accounted for approximately two thirds and temperate and boreal agricultural soils for one third of the area. Forestry-drained soils had a negligible effect. Half of the cooling effect was offset by the warming effect at the beginning.

3.3. The Effect of Trees

The dynamics of the C storage in tree biomass and wood products in the Finnish forestry-drained peatlands were very different between the management scenarios (Figure 4). In the abandonment scenario, the C storage tripled in 100 years. Changes were much smaller in the forestry scenario, as the initial stem volume was already close to the rotation mean at most site types (Table 3). In the abandonment and rewetting scenario, only a slight decrease in C storage occurred due to the decrease in wood product storage. In the clear-cut and rewetting scenario, two thirds of the aboveground C storage was lost during the first year, as the majority of the C in the tree stems and crowns was released as CO2. Both the initial C storage and the changes occurring were approximately twofold in the nutrient-rich category compared to the nutrient-poor category.

Figure 5. Upper: Radiative forcing (RF) scenarios for soil and soil + tree effects (Equations 2–5) of rewetting 1 ha of Finnish forestry-drained peatland. In addition, the RF scenario of abandoning forest (A–F, Equation 6) is presented. Lower: The share (%) of the cooling effect (reduction of CO2 and N2O emissions) that is offset by the warming effect (increase in CH4 emissions, decrease in tree biomass and wood product CO2 sink). F = forestry; A = abandonment; CC + RW = clear-cut and rewetting; and A + RW = abandonment & rewetting.
Tree biomass and wood product C storage dynamics strongly affected the RF scenario caused by rewetting (Figure 5). In the case of comparing rewetting to abandonment, the effect was on the climate-warming side for over a century. Comparing to forestry, clear-cut and rewetting needed nearly a 100 years before reaching zero. During the first decades after rewetting, the warming effects were multifold compared to the cooling effects in all these cases.

Comparing abandonment and rewetting to forestry showed a different result (Figure 5). While the tree stand and wood product effect shifted the RF upward even there, it delayed the change from warming to cooling for only 10–20 years. The effect of abandonment without rewetting was expectedly cooling and was slowly saturating toward the end of the scenario.

4. Discussion

The ability of peatland rewetting to mitigate climate change during the next decades depends strongly on the climate zone and current land use. Soil CO₂ emissions from tropical peatlands drained for croplands and plantations are so high (Table 1) that their successful rewetting results in virtually instant climate cooling (Figure 2). The increased CH₄ emissions offset only a few percent of the cooling. These values for rewetted peatland do not include CH₄ emissions from the trees, which may be substantial in tropical wetland forests (Covey & Megonical, 2019; Pangala et al., 2013). However, even if these quadrupled the CH₄ emissions of rewetted tropical peatland, the cooling effect would still be strong. We additionally need to remember that only the peat loss through decomposition is included in the emission factor used in our analysis. In addition to decomposition, peat fires release large amounts of CO₂ from drained tropical peat soils (Gaveau et al., 2014; Page et al., 2002), which further underlines the importance of rewetting in decreasing CO₂ emissions and consequent RF.

Those temperate and boreal drained peatlands that are under agriculture have the potential to mitigate climate change by rewetting (Figure 2). However, due to approximately 50% lower peat loss than under a tropical climate (Table 1), increased CH₄ emissions can offset a major part of the cooling effect during the first years and decades. Thus, peatlands that are likely to have low CH₄ emissions after rewetting should be prioritized as targets for rewetting. In addition, the soil CO₂ emissions decrease more or less linearly with a rising groundwater table, but CH₄ emissions largely increase only when the water table is raised close to the soil surface or above it (Couwenberg et al., 2011; Tiemeyer et al., 2016). Thus, moderate rewetting that raises the water table to 10–20 cm below the soil surface may be considered a means to prevent a major portion of peat loss without causing high CH₄ emissions. Removal of the nutrient-rich topsoil has also been suggested as an effective means to decrease CH₄ emissions following rewetting, especially when the site has been heavily fertilized during agricultural use (Harpenlager et al., 2015; Zak et al., 2018).

Contrary to agricultural peatlands, the possibility of mitigating climate change during the next decades by rewetting temperate and boreal forestry-drained peatlands is very limited (Figures 2, 3, and 5). The current soil CO₂ and N₂O emissions are so low that even a modest increase in CH₄ emissions can offset the cooling effect for decades. If the tree biomass and wood product C storage decreases considerably, reaching a climate-cooling effect is further delayed.

Even though rewetting of forestry-drained peatlands contradicts with the mitigation of current climate change, it is clear that rewetting would be the best option for safeguarding peat C storage in the long run. If drainage is maintained, a peatland with a thick layer of peat may gradually lose much more C than any tree stand can store. Also, the warming climate is likely to enhance peat decomposition, leading to increasing CO₂ emissions from peat (Table 1). Additionally, if climate change leads to increasing occurrence of severe droughts (Dai, 2013; Jolly et al., 2015), the risk of releasing great amounts of C to the atmosphere in forest and peat fires increases. Peatland fires are already common in continental areas, for example, in many parts of Canada (Turetsky et al., 2004) and Russia (Sirin et al., 2018).

Even if not rewetted, forestry-drained peatlands should be kept as wet as possible, without endangering the growing tree stand. There are at least two ways to maximize wetness: (1) If forestry is continued, ditch depth should be as limited as possible while still keeping the water table deep enough (mean growing season water table depth approximately 30 cm; Sarkkola et al., 2012) for reasonable tree growth. Keeping the water table at 30 cm instead of 40 cm may decrease net CO₂ emissions by approximately 0.5 t ha⁻¹ year⁻¹ (Ojanen & Minkkinen, 2019) without increasing CH₄ emissions (Ojanen et al., 2010).
If a forestry-drained peatland is abandoned without active rewetting, drainage ditches will gradually deteriorate over decades due to peat subsidence and natural blocking of ditches (Sikström & Hökkä, 2016). In this study, we assumed constant soil greenhouse gas emissions and tree growth conditions after abandonment, but in reality, abandonment would lead to a gradual decrease in both factors due to the rising water table. Thus, abandonment may combine the tree biomass CO₂ sink during the first decades (Figure 5) with preserving most of the peat. However, keeping the tree stand may warm the climate locally, as forest albedo is lower than that of open mire (Gao et al., 2014; Lohila et al., 2010). Yet, part of this warming may be offset by the higher formation of aerosols and clouds, as trees are important sources of volatile organic compounds (Teuling et al., 2017; Tunved et al., 2006).

As shown by our results (Figure 5), the effect of tree biomass and wood product C storage on the climate strongly depends on how trees are managed in rewetting versus no-rewetting scenarios. Further, the initial volumes, volume growths, and maximum volumes of unmanaged stands dictate how large and how rapidly changes in C storage are possible. All these naturally depend on climate, peatland type, and management history, which are highly variable between countries. Thus, our results on trees cannot be directly extended outside Finland. However, we can state that the management of trees may be crucial, at least when emissions from drained peat soil are relatively low (Table 1). Further studies are needed to judge whether tree management can be of importance under more intensive land use and a warmer climate. There, soil emissions are much higher (Table 1), but on the other hand, the growth potential of trees is also higher.

We estimated that global rewetting of drained peat soils during the next 20 years would decrease RF by 70 mW (m² Earth)⁻¹ by the end of the following 100 years (Figure 3), due to the major effect in tropical peatlands and temperate and boreal agricultural peatlands. Temperate and boreal forestry-drained peat soils played a negligible role in this result. Also, assuming a similar effect of trees as in Finland (Figure 5), 10.6 million ha of boreal and temperate forestry-drained peatlands (Table 2) would together offset the benefit by only a few percent. Thus, by rewetting all peatlands we could, for example, mitigate 15% of the current warming caused by anthropogenic methane emissions, that is, 0.48 W (m² Earth)⁻¹ (Myhre et al., 2013a).

The importance of peatland rewetting for climate change mitigation is well demonstrated also by their current emissions. Despite coarse and somewhat uncertain global area estimates for drained peatlands (Barthelmes, 2018; Joosten, 2010), drained peatlands are a globally important source of CO₂ and N₂O. Multiplying our area estimates (Table 2) by the IPCC emissions factors (Table 1) gives a rough estimate of 1 Gt of CO₂ equivalents per year (GWP₅₈) for soil greenhouse emissions. This emission corresponds to approximately ¼ of total emissions from land use, land use change, and forestry (Olivier et al., 2017), even though the area of drained peatlands corresponds to only 2% of the Earth’s land area. Joosten (2010) and Leifeld and Menichetti (2018) estimated twice as high global emissions for drained peatlands, 2 Gt of CO₂ equivalents per year, due to a higher area estimate (50 vs. 33 million ha) and the inclusion of CO₂ emissions from tropical peat fires.

As the rapid rewetting of up to 50 million ha of drained peatlands is a huge effort, identifying the most prominent peatlands for climate change mitigation would be crucial for efficient resource allocation. Our results clearly indicate that tropical and agricultural peatlands have the highest potential for climate change mitigation by rewetting. Yet, it should be kept in mind that the emission factors applied in this study (Table 1) are mean values for wide land use and climate categories. Huge variation in emissions occurs within each drained category (Couwenberg et al., 2010, 2011; Hooijer et al., 2010, 2012; Ojanen & Minkkinen, 2019; Tiemeyer et al., 2016). Also, the potential of tree effects is case specific. Feasible and unfeasible targets for rewetting may be found within any category. Other means for reducing greenhouse gas emissions should be sought for peatlands where rewetting is unfeasible.

5. Conclusions

Peatland rewetting is generally beneficial and important for mitigating climate change during upcoming decades. Tropical and agricultural peatlands in particular have a high potential to mitigate climate change: the climate-cooling effect of preventing peat loss is larger than the climate-warming effect of increased methane emissions. Abandoning tree stands without active rewetting is the best option for boreal
forestry-drained peatlands: Peat loss prevented by rewetting is so low that increased methane emissions may offset the cooling effect for decades. The decrease in tree and wood product carbon storage further delays the onset of the cooling effect.

Data Availability Statement

All data necessary to reproduce the calculations (Tables 1–5) and the results (data for Figures 1–5) are available through Figsshare (Ojanen & Minkkinen, 2020).

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References

Barthelmes, A. (Ed.) (2018). Reporting greenhouse gas emissions from organic soils in the European Union: Challenges and opportunities. Policy brief (pp. 1–16). Paper presented at Proceedings of the Greifswald Mire Centre.

Couwenberg, J., Dommann, R., & Joosten, H. (2010). Greenhouse gas fluxes from tropical peatlands in south-east Asia. Global Change Biology, 16, 1715–1732. https://doi.org/10.1111/j.1365-2486.2009.02016.x

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärsch, S., Dubovik, D., et al. (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia, 674, 67–89. https://doi.org/10.1007/s10750-011-0729-x

Couvreur, T., Beekmann, H., & Megorical, P. (2019). Methane production and emissions in trees and forests. New Phytologist, 222, 35–51. https://doi.org/10.1111/nph.15624

Dai, A. (2013). Increasing drought under global warming in observations and models. Nature Climate Change, 3, 51–58. https://doi.org/10.1038/nclimate1633

Dommann, R., Froliking, S., Jeitsch Thömmes, A., Joos, F., Couwenberg, J., & Glaser, P. H. (2018). A radiative forcing analysis of tropical peatlands before and after their conversion to agricultural plantations. Global Change Biology, 24, 5515–5533. https://doi.org/10.1111/gcb.14406

Etminan, M., Myhre, G., Highwood, E. J., & Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophysical Research Letters, 43, 614–623. https://doi.org/10.1002/2016GL071930

Evans, C., Artz, R., Moxley, J., Smyth, M.-A., Taylor, E., Archer, N., et al. (2017). Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy, Centre for Ecology and Hydrology, Bangor. Available at: http://hdl.handle.net/10197/10153

Evans, C., Renou-Wilson, F., & Strack, M. (2015). The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. Aquatic Sciences, 78, 573–590. https://doi.org/10.1007/s00027-015-0447-y

Froliking, S., & Roulet, N. (2007). Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. Global Change Biology, 13, 1079–1088. https://doi.org/10.1111/j.1365-2486.2007.01339.x

Froliking, S., Roulet, N., & Fuglestvedt, J. (2006). How northern peatlands influence the Earth’s radiative budget: Sustained methane emission versus sustained carbon sequestration. Journal of Geophysical Research, 111, G01008. https://doi.org/10.1029/2005JG000091

Gao, Y., Markkanen, T., Backman, L., Henttonen, H. M., Pietikäinen, J.-P., Mäkelä, H. M., & Laaksonen, A. (2014). Biogeophysical impacts of peatland forestation on regional climate changes in Finland. Biogeosciences, 11, 7251–7267. https://doi.org/10.5194/bg-11-7251-2014

Gaveau, D., Salim, M., Hergoulalc’h, K., Locatelli, B., Sloan, S., Wooster, M., et al. (2014). Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: Evidence from the 2013 Sumatran fires. Scientific Reports, 4, 6112. https://doi.org/10.1038/srep06112

Gustavsen, H. G., & Päivänen, J. (1971). Virgin peatland forests in Finland. Heikurainen, L. (1971). Virgin peatland forests in Finland. Acta Agraria Fennica, 123, 11–26.

Hirahshi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G. (Eds.). (2014a). 2013 Revised supplementary methods and good practice guidance arising from the Kyoto protocol. Switzerland. Available at: IPCC. http://www.ipcc-nggip.iges.or.jp/public/kpg/index.html

Hirahshi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G. (Eds.). (2014b). 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Switzerland. Available at: IPCC. https://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html

Hökkä, H., Repola, J., & Laine, J. (2008). Quantifying the interrelationship between tree stand growth rate and water table level in drained peatlands: A case study within Central Finland. Canadian Journal of Forest Research, 38(7), 1775–1783. https://doi.org/10.1139/X08-028

Hommelberg, J., Schmid, H. P., Deéléter, M., & Werle, P. (2014). Can a bog drained for forestry be a stronger carbon sink than a natural bog forest? Biogeosciences, 11, 3477–3493. https://doi.org/10.5194/bg-11-3477-2014

Hooijer, A., Page, S. E., Canadell, J. G., Silvis, M., Kwadijk, J., Wösten, H., & Etminan, M. (2018). A radiative forcing analysis of tropical peatlands in south-east Asia. Biogeosciences, 15, 1071–1086. https://doi.org/10.5194/bg-15-1071-2018

Hooijer, A., Page, S. E., Jauhiainen, J., Lee, W. A., Lu, X. X., Idris, A., & Anshari, G. (2012). Subsidence and carbon loss in drained tropical peatlands. Biogeosciences, 9, 1053–1071. https://doi.org/10.5194/bg-9-1053-2012

Ihalainen, A. (2013). Metsähallitus and Metsäkeskuksen Metsähallituksen Information and Knowledge Services for Data Management. Available at: http://tietokantatalo.metsa.fi

Intergovernmental Panel on Climate Change (IPCC) (2018). Summary for Policymakers. In Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (1–24). Geneva, Switzerland: World Meteorological Organization. www.ipcc.ch

Jolly, W. M., Cochrane, M., Freeborn, P., Holden, Z., Brown, T., Williamson, G., & Bowman, D. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications, 6, 7537. https://doi.org/10.1038/ncomms8537
Joosten, H. (2010). The global peatland CO2 picture: Peatland status and drainage related emissions in all countries of the world. Wetlands International. Available at: www.wetlands.org

Joosten, H., Tapio-Biström, M. & Tol, S. (eds.) (2012). Peatlands—Guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Second Edition. Food and Agriculture Organization of the United Nations and Wetlands International. Mitigation of Climate Change in Agriculture (MICCA) Programme. Available at: www.fao.org/docrep/015/an762e/an762e.pdf

Juutonen, H., Hynminen, A., Nieminen, M., Tuomivirta, T., Tuttitala, E.-S., Nousiainen, H., et al. (2012). Methane-cycling microbial communities and methane emission in natural and restored peatlands. Applied and Environmental Microbiology, 78(17), 6386-6389. https://doi.org/10.1128/AEM.00261-12

Komulainen, V.-M., Nykänen, H., Martikainen, P. J., & Laine, J. (1998). Short-term effect of restoration on vegetation change and methane emissions from peatlands drained for forestry in southern Finland. Canadian Journal of Forest Research, 28(3), 402–411.

Korhola, A., Ruppel, M., Seppä, H., Väliranta, M., Virtanen, T., & Weckström, J. (2010). The importance of northern peatland expansion to the late-Holocene rise of atmospheric methane. Quaternary Science Reviews, 29, 611–617. https://doi.org/10.1016/j.quascirev.2009.12.010

Korhonen, K. T., Halainen, A., Ahola, A., Heikkinen, J., Henttonen, H. M., Hotanen, J.-P., et al. (2017). Suomen metsät 2009-2013 ja niiden kehitys 1921–2013. Luonnonvara- ja biotalousen tutkimus, 59(2017), 1–86. Available at: http://urn.fi/URN:NBN:fi:201709186474

Koskinen, M., Maanavilja, L., Nieminen, M., Minkkinen, K., & Tuttitala, A.-S. (2016). High methane emissions from restored Norway spruce swamps in southern Finland over one growing season. Mires and Peat, 17. https://doi.org/10.19189/MaP.2015.OMB.202

Laine, J., Silvola, J., Tolonen, K., Alm, J., Nykänen, H., Vasander, H., et al. (1996). Effect of water-level drawdown on global climatic warming: Northern Peatlands. Ambio, 25(3), 179–184.

Lampela, M., Jauhiainen, J., Sarkkola, S., & Vasander, H. (2017). Promising native tree species for reforestation of degraded tropical peatlands. Forest Ecology and Management, 394, 52–63. https://doi.org/10.1016/j.foreco.2016.12.004

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., & Liski, J. (2004). Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management, 188, 211–224. https://doi.org/10.1016/j.foreco.2003.07.008

Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate modification strategies. Nature Communications, 9, 1071. https://doi.org/10.1038/s41467-018-03406-6

Lohila, A., Minkkinen, K., Laine, J., Savolainen, I., Tuovinen, J.-P., Korhonen, I., et al. (2010). Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. Journal of Geophysical Research, 115, G04011. https://doi.org/10.1029/2010JG001327

Luijendijk, P., Kühlköt, N., Tuomivirta, J.-P., Lohila, A., Minkkinen, K., Laurila, T., & Väliranta, M. (2017). Lateral expansion and carbon exchange of a boreal peatland in Finland resulting in 7000 years of positive radiative forcing. Journal of Geophysical Research: Biogeosciences, 122, 562–577. https://doi.org/10.1002/2016JG003749

Mäkipää, R., Tuovinen, J.-P., Lohila, A., Aurela, M., Juutinen, S., Laurila, T., et al. (2014). Development, carbon accumulation, and radiative forcing of a subarctic fen over the Holocene. The Holocene, 24(9), 1156–1186. https://doi.org/10.1177/0959683614538073

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Global Ecology and Conservation, 6, 67–78. https://doi.org/10.1016/j.gecco.2016.02.004

Minkkinen, K., Korhonen, R., Savolainen, I., & Laine, J. (2002). Carbon balance and radiative forcing of Finnish peatlands 1990–2010—The impact of forestry drainage. Global Change Biology, 8, 785–799.

Minkkinen, K., Laine, J., & Hökkä, H. (2001). Tree stand development and carbon sequestration in drained peatland stands in Finland—A simulation study. Silva Fennica, 35(1), 55–69. https://doi.org/10.14214/sf.603

Minkkinen, K., Ojanen, P., Penttilä, T., Aurela, M., Laurila, T., Tuovinen, J.-P., & Lohila, A. (2018). Persistent carbon sink at a boreal drained forest. Biogeosciences, 15, 3603–3624. https://doi.org/10.5194/bg-15-3603-2018

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013a). Anthropogenic and natural radiative forcing. In T. F. Stocker et al. (Eds.), Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (pp. 701–86). Cambridge, UK, and New York, NY. Available at: Cambridge University Press. www.climatechange2013.org and www.ipcc.ch

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013b). Anthropogenic and natural radiative forcing supplementary material. In T. F. Stocker et al. (Eds.), Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (pp. 701–86). Cambridge, UK, and New York, NY. Available at: Cambridge University Press. www.climatechange2013.org and www.ipcc.ch

Natural Resources Institute Finland (2018). Hakkukertymät ja puuston poistuma: Hakkukertymät ja puuston poistuma alueittain 2017. Retrieved from: http://urn.fi/URN:NBN:fi:2018–04–17

Neubauer, S., & Megenical, P. (2015). Moving beyond global warming potentials to quantify the climatic role of ecosystems. Ecosystems, 18, 1000–1013. https://doi.org/10.1007/s10021-015-9879-4

Ojanen, P., & Minkkinen, K. (2019). The dependence of net soil CO2 emissions on water table depth in boreal peatlands drained for forestry. Mires and Peat, 24, 27. https://doi.org/10.19189/MaP.2019.OMB.SIA.1751

Ojanen, P., & Minkkinen, K. (2020). Radiative forcing of peatland rewetting [Figsshare]. https://doi.org/10.6084/m9.figshare.1214583

Ojanen, P., Minkkinen, K., Laurila, T., & Penttilä, T. (2010). Soil-atmosphere CO2, CH4, and N2O fluxes in boreal drained-forestand peatlands. Forest Ecology and Management, 260, 411–421. https://doi.org/10.1016/j.foreco.2010.04.036

Oleszczuk, R., Regina, K., Stajdák, L., Höper, H., & Marygova, V. (2008). Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In M. Strack (Ed.), Peatlands and Climate Change (pp. 70–97). Finland: International Peat Society.

Olivier, J., Schure, K., & Peters, J. (2017). Trends in global CO2 and total greenhouse gas emissions: 2017 Report. The Hague. Available at: PBL Netherlands Environmental Assessment Agency. www.pbl.nl/en

Page, S., Rieley, J., Shotyk, Ø., & Weiss, D. (1999). Interdependence of peat and vegetation in a tropical peat swamp forest. Philosophical Transactions of the Royal Society, B: Biological Sciences, 354(1391), 1885–1897. https://doi.org/10.1098/rstb.1999.0529

Page, S., Siegert, F., Rieley, J., Boehm, V., Jaya, A., & Limin, S. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature, 420, 61–65. https://doi.org/10.1038/nature01131
Pangala, S., Moore, S., Hornibrook, E., & Guac, V. (2013). Trees are major conduits for methane egress from tropical forested wetlands. *New Phytologist*, *197*, 524–531. https://doi.org/10.1111/nph.12031

Raudsaar, N., Simion, K-L, & Valgepea, M. (eds.) (2017). Yearbook Forest 2016. Republic of Estonia Environment Agency.

Renou-Wilson, F., Wilson, D., Rigney, C., Byrne, K., Farrel, K. & Müller, C. (2018). Network monitoring rewetted and restored Peatlands/organic soils for climate and biodiversity benefits (NEROS). EPA Research Report, 236.

Rockström, J., Gaffney, O., Rogelj, J., Meinsmaussen, M., Nakicenovic, N., & Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, *355*(6331), 1269–1271. https://doi.org/10.1126/science.aah3443

Rogelj, J., Shindell, D., Jiang, K., Filti, S., Forster, P., Ginzbarg, V., et al. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In V. Masson-Delmoët et al. (Eds.). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (pp. 93–174). Reprinted from www.ipcc.ch

Rolfkop, N., Fell, H., & Zeitz, J. (2015). Organic soils in Germany, their distribution and carbon stocks. *Catena*, *133*, 157–170. https://doi.org/10.1016/j.catena.2015.05.004

Sarkkola, S., Hikkä, H., Ahl, E., Koivusalo, H., & Nieminen, M. (2012). Depth of water table prior to ditch network maintenance is a key factor for tree growth response. *Scandinavian Journal of Forest Research*, *27*, 649–658. https://doi.org/10.1080/02827581.2012.689004

Seppälä, K. (1969). Kuusen ja männyn kasvun kehitys ojitetuilla turvemailla. Summary: Post-rewetting of organic soils.

Sirin, S., Medvedeva, M., Maslov, A., & Vozbrannaya, A. (2018). Assessing the land and vegetation cover of abandoned downy birch stands growing on well-drained peatlands. *Global Biogeochemical Cycles*, *32*(9), GB4014. https://doi.org/10.1029/2019GB006503

Sikström, U., & Hökkä, H. (2016). Interactions between soil water conditions and forest stands in boreal forests with implications for ditch network maintenance. *Silva Fennica*, *50*(1), 1416. https://doi.org/10.14214/sf.1416

Srin, S., Medvedeva, M., Maslov, A., & Vozbrannaya, A. (2018). Assessing the land and vegetation cover of abandoned fire hazardous and rewetted Peatlands: Comparing different multispectral satellite data. *Landscape*, *7*(2), 71. https://doi.org/10.1390/land7020071

Statistics Finland (2018). Greenhouse Emissions in Finland 1990 to 2016. National Inventory Report under the UNFCCC and the Kyoto Protocol.

Treuling, A., Taylor, C., Meriinka, J., Melsen, L., Miralles, D., Heerwaarden, C., et al. (2012). Observational evidence for cloud cover enhancement over western European forests. *Nature Communications*, *8*, 14,065. https://doi.org/10.1038/ncomms14065

Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, 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. https://doi.org/10.1111/gcb.13303

Tunved, P., Hansson, H.-C., Kerminen, V.-M., Ström, J., Dal Maso, M., Lihavainen, H., et al. (2006). High natural aerosol loading over boreal forests. *Science*, *312*, 261–264. https://doi.org/10.1126/science.1123052

Turetsky, M., Amiro, B., Bosch, E., & Bhatti, J. (2004). Historical burn area in western Canadian peatlands and its relationship to fire weather indices. *Global Biogeochemical Cycles*, *18*, GB4014. https://doi.org/10.1029/2004GB002222

Uri, V., Kukumägi, M., Aanaar, J., Varki, M., Becker, H., Morozov, G., & Karoles, K. (2017). Ecosystems carbon budgets of differently aged drained peatlands. *Forest Ecology and Management*, *399*, 82–93. https://doi.org/10.1016/j.foreco.2017.05.023

Vahtera, E., Aarne, M., Ihalainen, A., Mäki-Simola, E., Peltola, A., Torvelainen, J., et al. (2018). Finnish forest statistics. Natural Resources Institute Finland. Available at: http://urn.fi/URN:NBN:fi-fe201902043966

Vanselow-Algan, M., Schmidt, S. R., Greven, M., Flence, C., Kutzbach, L., & Pfeiffer, E.-M. (2015). High methane emissions dominated annual greenhouse gas balances 30 years after bog rewetting. *Biogeochemistry*, *124*(4), 4361–4371. https://doi.org/10.5194/bg-12-4361-2015

Wilson, D., Blain, D., Couwenberg, J., Evans, C., Murdiyarso, D., Page, S., et al. (2016). Greenhouse gas emission factors associated with phosphorus and dissolved organic matter and lowers methane emissions from rewetted peatlands. *Journal of Applied Ecology*, *55*, 311–320. https://doi.org/10.1111/1365-2664.12931

Yu, Z. (2011). Holocene carbon flux histories of the world's peatlands: Global carbon-cycle implications. *The Holocene*, *21*(5), 763–774. https://doi.org/10.1177/0959683610386982

Zak, D., Goldhammer, T., Cabezas, A., Gelbrecht, J., Gurke, R., Wagner, C., et al. (2018). Top soil removal reduces water pollution from phosphorous and dissolved organic matter and lowers methane emissions from rewetted peatlands. *Landscape and Urban Planning*, *180*, 21–30. https://doi.org/10.1016/j.landurbplan.2018.04.008

Rogelj, J., Shindell, D., Jiang, K., Filti, S., Forster, P., Ginzbarg, V., et al. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In V. Masson-Delmoët et al. (Eds.). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (pp. 93–174). Reprinted from www.ipcc.ch