Global
Biogeochemical Cycles

RESEARCH ARTICLE
10.1029/2019GB006503

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

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Key Points:

- Rewetting of tropical peat soils resulted in immediate cooling
- In temperate and boreal agricultural peat soils, methane emissions offset a major part of the cooling for the first decades
- Abandoning tree stands may be more beneficial than rewetting in temperate and boreal forestry-drained peatlands

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Citation:
Ojanen, P., & Minkkinen, K. (2020). Rewetting offers rapid climate benefits for tropical and agricultural peatlands but not for forestry-drained peatlands. *Global Biogeochemical Cycles*, *34*, e2019GB006503. https://doi.org/10.1029/2019GB006503

Received 17 DEC 2019
Accepted 13 JUN 2020
Accepted article online 24 JUN 2020

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_2O) emissions, as

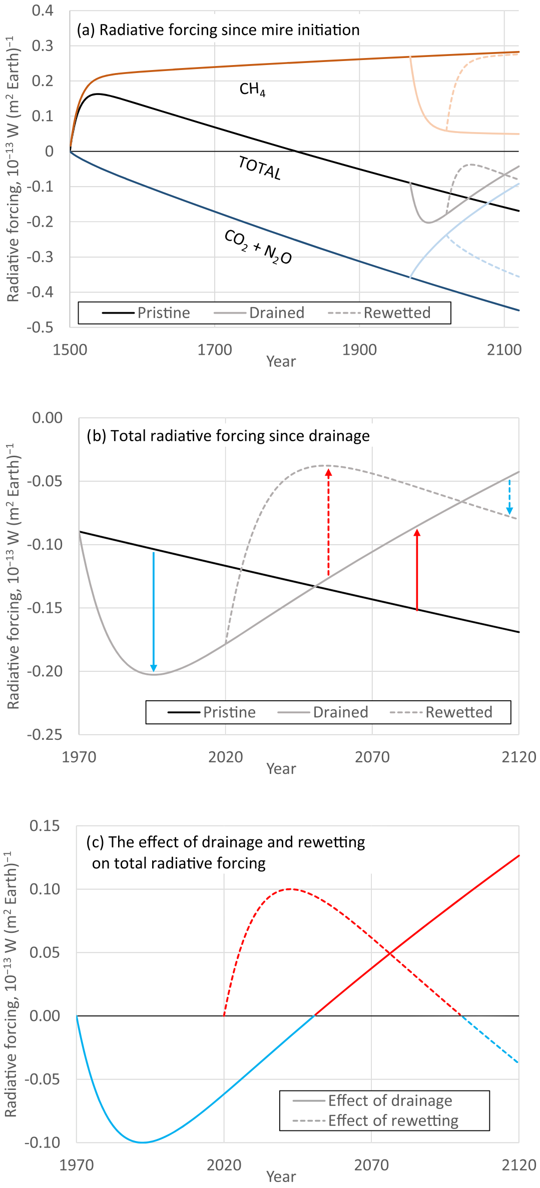

Figure 1. (a) An example of radiative forcing caused by the soil CO_2 sink and CH_4 and N_2O source of mire development over 620 years, since mire initiation at year 1,500, and alternative scenarios due to drainage at 1970 and rewetting at 2020. The applied gas sinks (−) and sources (+) for CO_2, CH_4, and N_2O are realistic values for one m^2 of peatland soil but are chosen for illustrative purposes and do not represent any specific peatland type or climate: Undrained and rewetted: −130, +7, and +0.1 g $year^{-1}$ of gas; drained: +130, ±0, +0.2 g $year^{-1}$ of gas. (b) Magnification of figure a, for 1970–2120. Cooling and warming effects of drainage and rewetting are shown with blue and red arrows. (c) The effects of drainage (= drained − undrained) and rewetting (= rewetted − drained); the effect of rewetting is the object of this study. Blue and red colors are used to emphasize the cooling and warming phases. See section 2.4 for the calculation of radiative forcing.

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

Table 1

Soil Emission Factors (t ha^{-1} year^{-1} of gas) for CO_2, CH_4, and N_2O at Drained and Rewetted Peatlands and the Effect of rewetting (= rewetted − drained) According to Wilson et al. (2016)

		Drained			Rewetted			Effect		
Zone	Land use	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
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	−0.0004

Note. The emissions for CH_4 and N_2O are on-site emissions, including CH_4 emissions from ditches in drained peatlands. For CO_2, 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 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 CO_2 sink to the tree biomass. This CO_2 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 CO_2, CH_4, and N_2O 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:

$$\text{Effect of rewetting} = \text{net emission at rewetted peatland} - \text{net emission at drained peatland} \qquad (1)$$

In this study, the effect of rewetting was assumed to be instantaneous and thereafter constant. Emissions of CO_2, CH_4, and N_2O 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).

The CO_2 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 CO_2 (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 CH_4 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 CO_2, CH_4, and N_2O (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.

Table 2

Country-Specific Areas (1,000 ha) of Drained Peatlands Divided Into Different Land Use Categories

	Forest/tropical plantation					
Country	Total	Nutrient-poor	Nutrient-rich	Cropland	Grassland	Sources/sum
Boreal						
Canada	0			6.08	0	CRF
Finland	4,648.2	2,829.9	1,818.3	254.77	68.49	NIR, CRF, Korhonen et al. (2017)
Iceland	3.63	3.63		56.31	367.45	CRF
Norway	253	51	202	63.18	2.4	NIR, CRF, Lise Dalsgaard
Russia	1950.2			2,507.5	1,758.1	CRF
Sweden	621	310	311	135	6	NIR, CRF, Björn Hånell
Sum	7,476.03	3,194.53	2,331.3	3,022.84	2,202.44	12,701.31
Temperate						
Australia	0			12.66	48.88	CRF
Austria	0			0	12.95	CRF
Belarus	178.72			1381.5	28.62	CRF
Belgium	0			1.9	0.82	CRF
Canada	0			6.08	0	CRF
Croatia	0			2.46	0.23	CRF
Denmark	36.45634			112.7802	37.42361	CRF, NIR
Estonia	312.5		312.5	21.02	44.13	CRF, Raudsaar et al. (2017)
France	32.28			16.26	76	CRF
Germany	186.75	39.16	147.58	380.66	862.88	NIR, Roßkopf et al. (2015)
Greece	0			6.66	0	CRF
Hungary	6.46			0	0	CRF
Ireland	321.93	321.93		1.235	374.69	Renou-Wilson et al. (2018), David Wilson
Italy	0			24.69	0.79	CRF
Japan	0			23.9	56.56	CRF, NIR
Latvia	485.28	101.42	383.86	92.96	45.62	CRF, Andis Lazdiņš/Latvian forest inventory
Liechtenstein	0			0.12	0.06	CRF
Lithuania	174.3	57.4	116.9	14.97	158.96	CRF, NIR
The Netherlands	0			92.65	287.88	CRF, NIR
New Zealand	4.74			10.5	175.94	CRF, NIR
Poland	258.02			533.42	148.04	CRF
Romania	95.33			6.39	5.04	CRF, NIR
Slovenia	0.76			2.5	0	CRF
Sweden	350	68	282		13	CRF, NIR
Switzerland	3.96			10.45	6.91	CRF
Turkey	0			18.83	3.01	CRF, NIR
Ukraine	192.7			108.52	369.83	CRF
United Kingdom	439	90.87	348.13	194	565	Evans et al. (2017), Chris Evans, Rebekka Artz
USA	70.85			688.81	637.24	CRF, NIR
Sum	3,150	678.79	1,590.97	3,765.93	3,960.50	10876.46
Tropical						
Malaysia, Indonesia, China	4,286.07			5,289.50		Miettinen et al. (2016), Oleszczuk et al., 2008
Sum	4,286.07			5,289.50		9,575.57
Global sum	14,912			12,078	6,163	33,153.34

Note. The division between nutrient-poor and nutrient-rich sites is given for forested peatlands when available from the sources. The varying precision of the areas is due to the varying precision of sources. The Sources are as follows: National Inventory Submissions for 2017 (https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017) consisting of country-specific national inventory reports (NIR) and common reporting format tables (CRF), other publications, and researchers.

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

Table 3
Initial Stem Volume and Growth[1], Maximum Stem Volume of Unmanaged Forest[2], Rotation-Mean Stem Volume of Managed Forest[2], Area[1], and Areal Share of Pine-Dominated Forests[1]

Site type	Initial volume $m^3\ ha^{-1}$	Initial growth $m^3\ ha^{-1}\ year^{-1}$	Max volume $m^3\ ha^{-1}$	Mean volume $m^3\ ha^{-1}$	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	–	–	–	–	12	–
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	–	–	–	–	19	–
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	–	–	–	–	12	–
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	–	–	–	–	46	–

Note. Site types divide the area into productive forests (rotation-mean stem volume growth ≥ 1 $m^3\ ha^{-1}\ year^{-1}$) of declining fertility (herb-rich > *Vaccinium myrtillus* > *Vaccinium vitis-idaea* > dwarf shrub > *Cladina*), low-productive forests (rotation-mean stem volume growth < 1 $m^3\ ha^{-1}\ year^{-1}$), and unproductive, treeless areas. Sources: [1]Finnish National Forest Inventory for 2009–2013 (Korhonen et al., 2017; Antti Ihalainen/Natural Resources Institute Finland). [2]Minkkinen et al. (2001).
*Maximum and mean stem volumes not available in the original publication, estimated through linear regressions with initial growth.

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:

$$\text{Effect of rewetting} = \text{C storage in clear} - \text{cut and rewetting scenario} - \text{C storage in forestry scenario} \quad (2)$$

$$\text{Effect of rewetting} = \text{C storage in clear} - \text{cut and rewetting scenario} - \text{C storage in abandonment scenario} \quad (3)$$

Table 4
Additional Parameters Used for Calculating Tree Biomass and Wood Product C Storages

Parameter and usage	Value	Source
Ratio of mean annual tree stem volume increment and stem volume growth 2010–2017: used to calculate the initial stem volume increments in the forestry scenario	0.28	Natural Resources Institute Finland (2018)
Biomass expansion factor: used to convert stem volumes to stem, aboveground, and total biomasses and further C storages	t dry mass/m^3 stem volume	Lehtonen et al. (2004)
Pine-dominated stands, total	0.71	
Pine-dominated stands, aboveground	0.56	
Pine-dominated stands, stem	0.37	
Other stands, total	0.83	
Other stands, aboveground	0.65	
Other stands, stem	0.37	
Ratio of wood product C storage and tree biomass C storage: used to calculate the wood product C storage in the forestry scenario and initial wood product C storage in other scenarios based on tree biomass C storage	0.205	Minkkinen et al. (2002)
Life times of various wood products and their share in wood product C storage (2016): used to calculate the development of wood product C storage in scenarios other than forestry.	τ, years/share	Statistics Finland (2018)/ Hiraishi et al. (2014a)
Sawn wood	35/0.78	
Wood panels	25/0.10	
Paper and paperboard	2/0.11	
Merchantable share of stand stem volume: used to calculate the stem volume that is utilized to produce wood products after clear-cutting the peatland at rewetting	0.894	Ihalainen (2013)
Share of merchantable stem biomass that ends up as sawn wood/wood panels/paper and paperboard: used to calculate how much of the stem biomass used to produce wood products ends up into product C storage after clear-cutting the rewetted peatland	0.15/0.02/0.38	Vaahtera et al. (2018)

$$\text{Effect of rewetting} = \text{C storage in abandonment and rewetting scenario} - \text{C storage in forestry scenario} \tag{4}$$

$$\text{Effect of rewetting} = \text{C storage in abandonment and rewetting scenario} - \text{C storage in abandonment scenario} \tag{5}$$

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

$$\text{Effect of abandonment} = \text{C storage in abandonment scenario} - \text{C storage in forestry scenario} \tag{6}$$

Finally, the effect of rewetting (or abandonment) on C storage was converted to a 100-year scenario of CO_2 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:

$$\text{Emission}(n) = \text{C storage}(n) - \text{C storage}(n-1) \tag{7}$$

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 (pine vs. other species) 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).

Table 5

Radiative Forcing Time Series Due to Greenhouse Gas Emissions and Removals Were Calculated Based on the Current IPCC Radiative Efficiencies (RE, 10^{-13} W (m^2 Earth)$^{-1}$ (kg gas)$^{-1}$), Indirect Effects Multipliers, and Atmospheric Lifetimes (Time Constant τ, Years) for CO_2, CH_4, and N_2O (Myhre et al., 2013a, 2013b)

Gas	RE	Indirect effects	Fraction	τ
CO_2	0.0176	1	0.2173	∞
			0.2240	394.4
			0.2824	36.54
			0.2763	4.304
CH_4	1.58	1.53	1	12.4
N_2O	3.85	0.93	1	121

Note. An updated value by Etminan et al. (2016) was applied for the RE of CH_4. Carbon dioxide emission/removal was divided into four fractions with different lifetimes.

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 CO_2, CH_4, and N_2O (= 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 CO_2 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 CO_2 resulting from the atmospheric decay of CH_4 was taken into account by including it into the RF of CH_4 in the calculation. This effect of CH_4-derived CO_2 is demonstrated as a slow rise in the RF of constant CH_4 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 (CO_2 and N_2O removals) and warming (CH_4 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:

$$\text{Warming/cooling ratio} = -[\text{RF}\ (CH_4) + \text{RF}\ (\text{tree stand} + \text{wood product})]/[\text{RF}\ (CO_2) + \text{RF}(N_2O)] \times 100\% \tag{8}$$

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 CH_4 emissions offset only a few percent of the cooling by decreasing the CO_2 and N_2O 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 CH_4

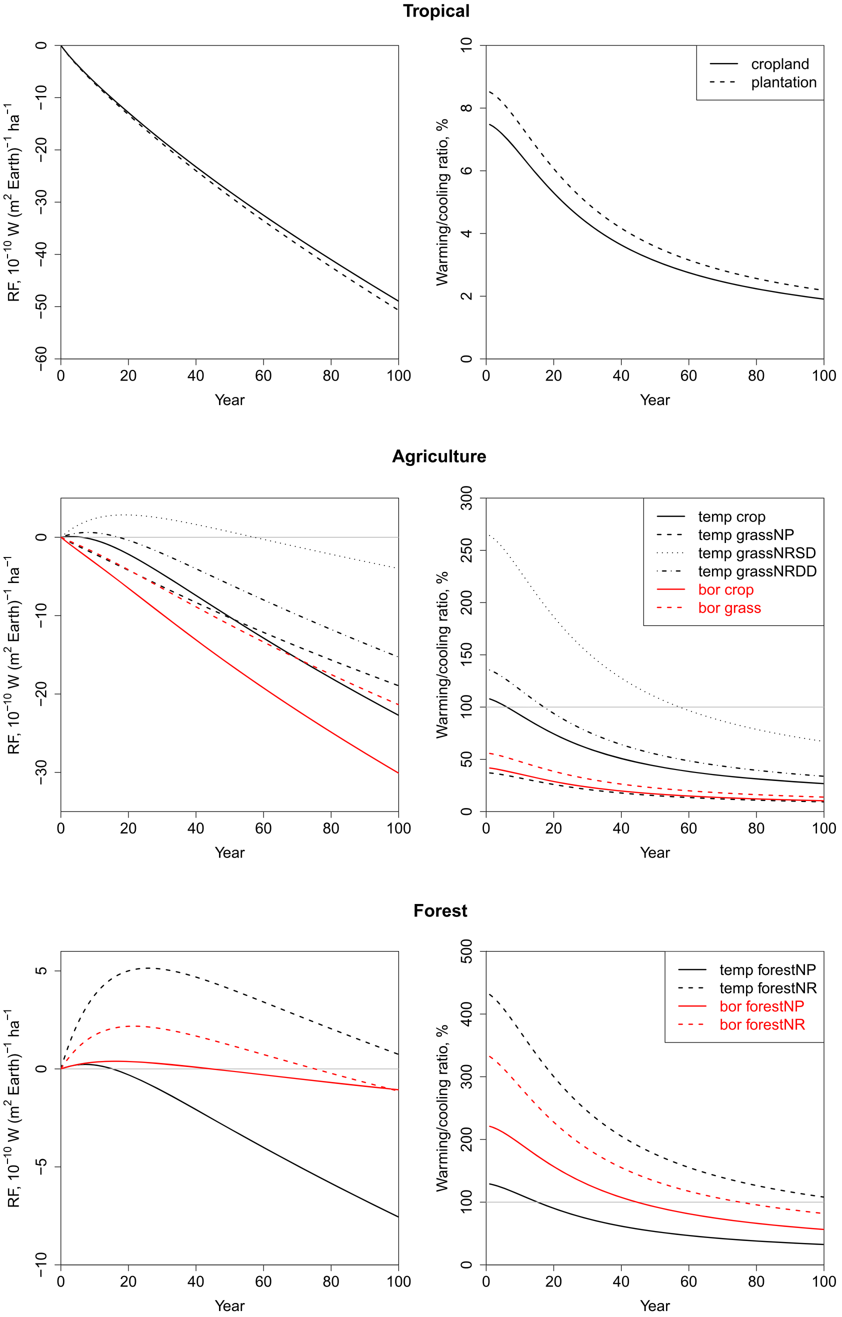

Figure 2. (left) Radiative forcing (RF) scenarios for rewetting 1 ha of drained peat soil in different land uses and climates. Right: The share (%) of the cooling effect (reduction of CO_2 and N_2O emissions) offset by the warming effect (increase in CH_4 emissions). Temp = temperate; bor = boreal; crop = cropland; grass = grassland; forest = forestry drained; NP = nutrient poor; NR = nutrient rich; SD = shallow drainage; and DD = deep drainage.

emissions experienced a cooling net effect at the beginning. Temperate nutrient-rich shallow drained grassland soil with its low decrease in CO_2 emissions and high increase in CH_4 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 CH_4 emissions offset over 100% of the cooling impact of decreased CO_2 and N_2O emissions for at least the first 40 years. Even 100 years after rewetting, the offset was at least 50%.

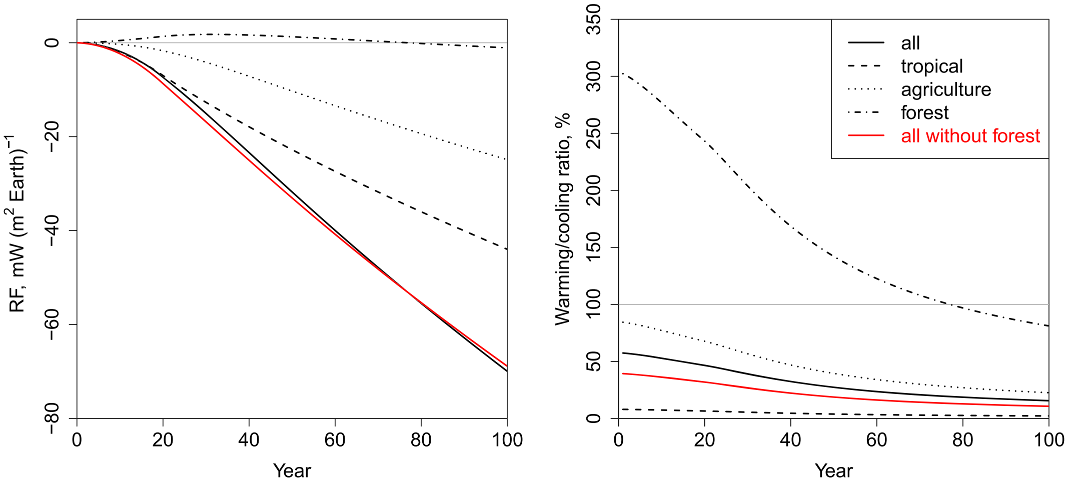

Figure 3. (left) The radiative forcing (RF) scenario for globally rewetting all the drained peat soils in 20 years. (right) The share (%) of the cooling effect (reduction of CO_2 and N_2O emissions) offset by the warming effect (increase in CH_4 emissions). Tropical = tropical croplands and plantations; agriculture = temperate and boreal croplands and grasslands; and forest = temperate and boreal forestry-drained peatlands.

In addition to the temporal dynamics, the magnitude of the climate cooling also varied (Figure 2). In the tropics, an RF of -50×10^{-10} W (m^2 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 -8×10^{-10} W (m^2 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 mW (m^2 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

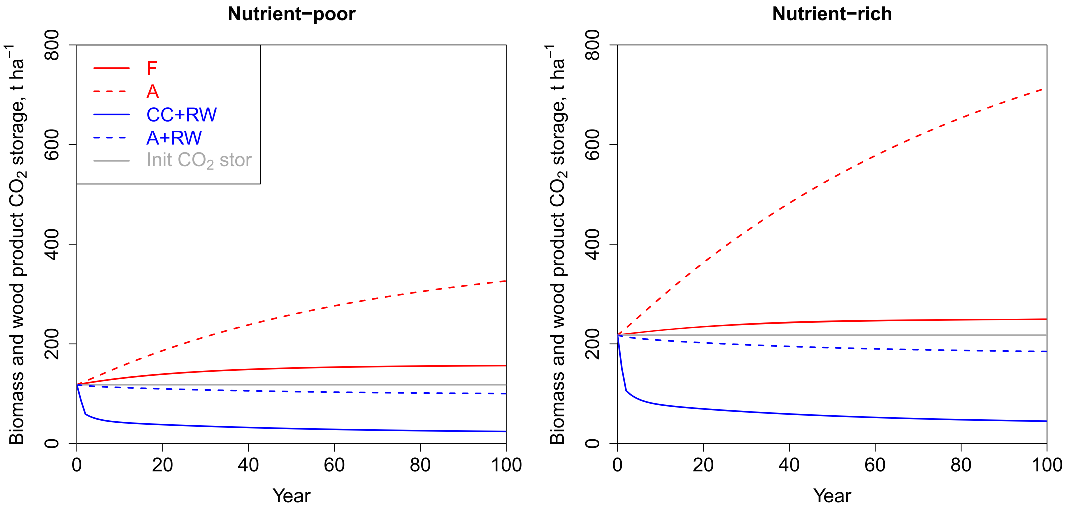

Figure 4. Country-scale mean tree stand and wood product carbon storage (as CO_2) scenarios for different forest management scenarios for nutrient-poor and nutrient-rich forestry-drained peatlands in Finland. F = forestry; A = abandonment; CC + RW = clear-cut and rewetting; A + RW = abandonment and rewetting; and Init CO_2 stor = carbon storage at year 0.

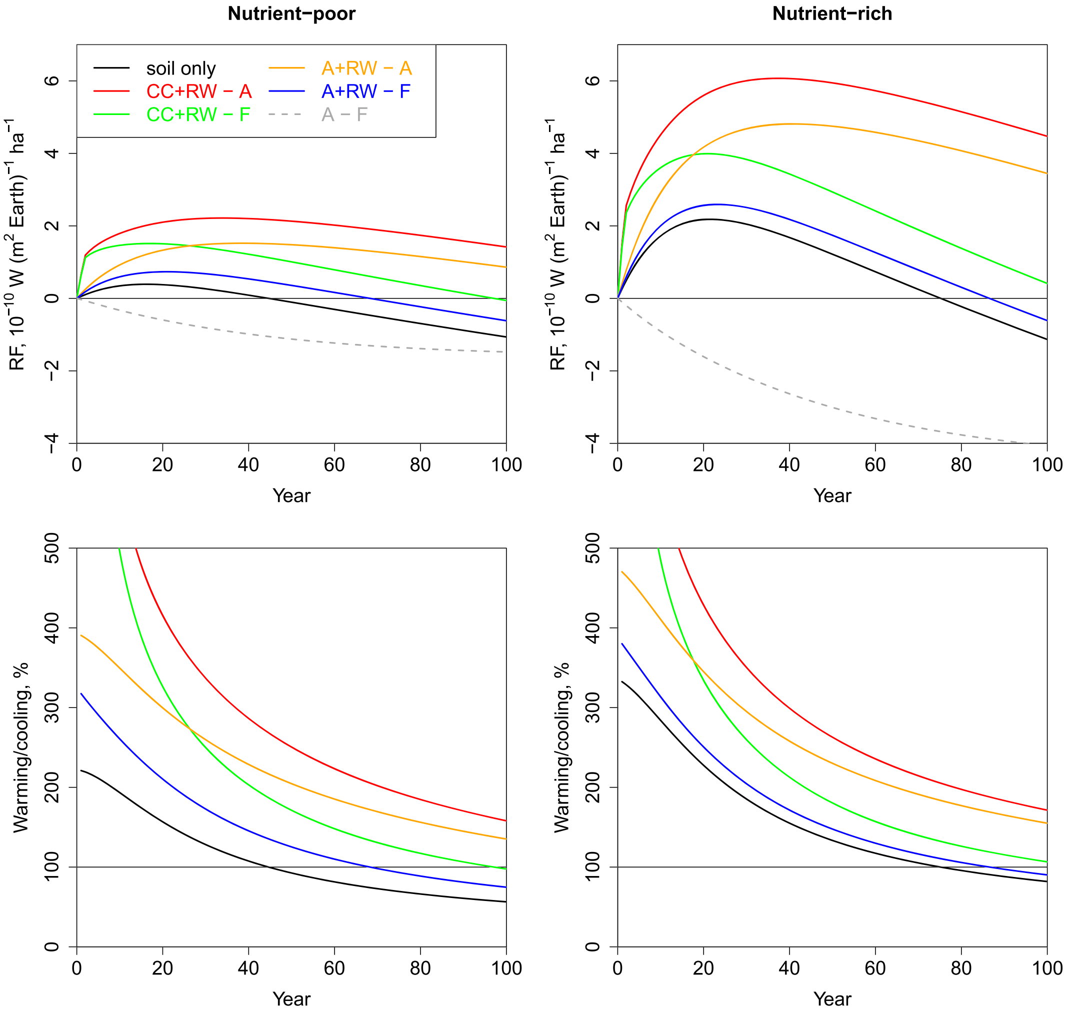

Figure 5. Upper: Radiative forcing (RF) scenarios for soil and soil + tree effects (Equations 2–5) of rewetting 1 ha of Finnish forestry-drained peatland. In addition, the RF scenario of abandoning forest (A–F, Equation 6) is presented. Lower: The share (%) of the cooling effect (reduction of CO_2 and N_2O emissions) that is offset by the warming effect (increase in CH_4 emissions, decrease in tree biomass and wood product CO_2 sink). F = forestry; A = abandonment; CC + RW = clear-cut and rewetting; and A + RW = abandonment & rewetting.

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 CO_2. Both the initial C storage and the changes occurring were approximately twofold in the nutrient-rich category compared to the nutrient-poor category.

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 CO_2 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 CH_4 emissions offset only a few percent of the cooling. These values for rewetted peatland do not include CH_4 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 CH_4 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 CO_2 from drained tropical peat soils (Gaveau et al., 2014; Page et al., 2002), which further underlines the importance of rewetting in decreasing CO_2 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 CH_4 emissions can offset a major part of the cooling effect during the first years and decades. Thus, peatlands that are likely to have low CH_4 emissions after rewetting should be prioritized as targets for rewetting. In addition, the soil CO_2 emissions decrease more or less linearly with a rising groundwater table, but CH_4 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 CH_4 emissions. Removal of the nutrient-rich topsoil has also been suggested as an effective means to decrease CH_4 emissions following rewetting, especially when the site has been heavily fertilized during agricultural use (Harpenslager 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 CO_2 and N_2O emissions are so low that even a modest increase in CH_4 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 CO_2 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 CO_2 emissions by approximately 0.5 t ha^{-1} $year^{-1}$ (Ojanen & Minkkinen, 2019) without increasing CH_4 emissions (Ojanen et al., 2010).

(2) 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 CO_2 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 $(m^2 \text{ Earth})^{-1}$ 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 $(m^2 \text{ Earth})^{-1}$ (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 CO_2 and N_2O. Multiplying our area estimates (Table 2) by the IPCC emissions factors (Table 1) gives a rough estimate of 1 Gt of CO_2 equivalents per year (GWP_{100}) 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 CO_2 equivalents per year, due to a higher area estimate (50 vs. 33 million ha) and the inclusion of CO_2 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 Figshare (Ojanen & Minkkinen, 2020).

Acknowledgments
Kone Foundation (Koneen Säätiö) funded the work of Paavo Ojanen. We thank Rebekka Artz, Lise Dalsgaard, Chris Evans, Björn Hånell, Jyrki Jauhiainen, Andis Lazdiņš, and David Wilson for their help in gathering the area estimates and Stella Thompson for language editing. Antti Ihalainen (Natural Resources Institute Finland) provided tree stand stem volume and stem volume growth data for the Finnish forestry-drained peatlands.

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