Mitig Adapt Strateg Glob Change (2025) 30:13
https://doi.org/10.1007/s11027-025-10203-2

ORIGINAL ARTICLE

Crediting peatland rewetting for carbon farming: some considerations amidst optimism

Jens Leifeld[1] · **Sonja M. Paul**[1] · **Miriam Gross-Schmölders**[1,2] · **Yuqiao Wang**[1,3] · **Chloé Wüst-Galley**[1]

Received: 17 April 2024 / Accepted: 20 January 2025 / Published online: 31 January 2025

Abstract

Peatland drainage is worldwide a major human-induced greenhouse (GHG) source and rewetting increasingly considered a silver bullet to not only reverse the climate burden of peatland management, but also recover other ecosystem functions. Peatland rewetting is therefore one key measure in the evolving frameworks for carbon farming projects and an important nature based solution. However, with regards to the time horizon of rewetting projects and possible project failure the climate effect of rewetting has not yet been systematically analysed. Here we simulate the radiative forcing of peatland rewetting, based on impulse response functions, by using exemplary calculations addressing different time horizons, GHG fluxes and duration of project success. Water table drawdown during or after a rewetting project displaces GHG emissions into the future, meaning that rewetting projects that at some stage fail provide no climate benefit in the long run. This has important repercussions for the creditability of peatland projects and underpins that the value of peatland rewetting as a mitigation instrument strongly depends on successful and permanent implementation of a high water table. Furthermore, we show that linking radiative forcing with project duration and GHG emission patterns allows rational calculation of biophysical discounting and propose how such discounting can be used to account for the risk of project failure in payments to carbon farming schemes.

Keywords Nature based solution · Carbon market · Non-permanence · Wetland · Methane · Switchover time

✉ Jens Leifeld
jens.leifeld@agroscope.admin.ch

1 Agroscope, Climate and Agriculture Group, Reckenholzsstrasse 191, 8046 Zurich, Switzerland

2 Environmental Geosciences, University of Basel, Bernoullistrasse 30/32, 4056 Basel, Switzerland

3 College of Agronomy, Henan Agricultural University, Pingan Road 218, Zhengzhou 450046, China

1 Introduction

Peatland drainage for agriculture or forestry is among the major sources of GHGs in the land use sector, accounting for approximately 2.0 Pg CO_2-equivalent per year (UNEP 2022). Rewetting is a suitable way to reduce GHG emissions from peatland management (Günther et al. 2020; Freeman et al. 2022; Darusman et al. 2023), and also provides other environmental as well as socio-economic benefits (Glenk et al. 2021). It is therefore considered an important nature based solution (NBS) within, for example, the carbon farming initiative of the European Union (EC 2022a), that aims at removing 310 Mt CO_2eq. by 2030 (EC 2021), or by the Indonesian government for improving the GHG and fire situation of drained tropical peatlands via the Indonesian peatland restoration agency (Ward et al. 2020). Accordingly, standards to account for the climate benefit of peatland rewetting have been developed (Joosten et al. 2015; VCS 2017; Koolstofmarkt 2020; IUCN 2023). Yet, there are pending questions with respect to quantifying the contribution of peatland rewetting to mitigation targets, particularly 1) how to quantify the role of methane in a way suitable for carbon crediting, 2) how to deal with a possible failure of rewetting in the context of carbon accounting (non-permanence), as well as how to reliably determine the time horizon for reaching net cooling after water table raise and 3) how to consider different amounts of carbon stored in peat that can be protected from decomposition by rewetting. These aspects have been partially addressed in existing schemes, typically by applying the widely used concept of global warming potentials and corresponding emission factors. However, there is a lack of a fully quantitative, biophysically-based approach that is also capable of assessing different time horizons, which are necessary to account for different lifetimes of GHGs in the atmosphere, peat carbon stocks, or different fluxes over time. Such an approach is also needed to provide the net effect of any scenario (i.e. atmospheric cooling vs. warming at any point in time) in addition to simply assessing the reduced GHG emissions, i.e. just the relative benefit, of a measure compared to a baseline (hereafter referred to as the climate benefit).

NBS typically build on increasing carbon storage in ecosystems or on reducing ecosystem GHG fluxes or both. In the case of peatland rewetting not only eventual carbon accrual by the ecosystem, but more so reduced GHG emission by preserving the peat from oxidation to CO_2 is the main climate incentive for converting the land use (Tanneberger et al. 2021; EC 2022b). One challenge in peatland rewetting projects is the co-existence of CO_2 and CH_4 emissions. With a raised water table, CO_2 emissions from peat decomposition decrease while CH_4 emissions increase and empirical driver-response relationships that underpin this trade-off have been developed (Tiemeyer et al. 2020; Evans et al. 2021; Huang et al. 2021). Methane is considered as a contributing GHG in some of the existing methodologies for peatland rewetting (Joosten et al. 2015; VCS 2017) and is addressed via the global warming potential (GWP) approach, whereby the radiative effect of a GHG relative to CO_2 is derived from integrating the associated radiative forcing of a pulse emission over 20 or 100 years (IPCC 2021). GWPs are time-dependent and denote a static approach. Their suitability for analysing dynamic emission scenarios, addressing variable time horizons or defining emission reduction targets has therefore been called into question (Neubauer and Megonigal 2015; Allen et al. 2018) and approaches that calculate radiative forcing directly are deemed more appropriate (Dommain et al. 2018; Ojanen and Minkkinen 2020). These have, however, not yet been analysed in the context of crediting CO_2 savings from NBS.

A further inherent issue to NBS such as carbon sequestration in soil or peatland rewetting is the temporary nature of carbon storage or GHG emission reductions. This is a primary barrier to the requirement of permanence settled in many carbon farming project schemes (Oldfield et al. 2022). In the case of peatlands, the outcome of rewetting as a measure strongly depends on the success of keeping the water table high. Rewetting is in principal transient, given that intentional (e.g., change in political regulations and incentives, changes in farmer's habits and preferences, changing tenure and ownership rights, fraud), as well as incidental (e.g., droughts, breaking of dams, invasion of plant species or pests, fire) events may turn the rewetted peatland into the previous or at least a less desired, drier stage. Technically, a project failure in the field of peatland rewetting represents a displaced emission. Approaches how to deal adequately with the problem of displaced (sometimes referred to as 'postponed') emissions in the context of carbon sequestration were already addressed early on (e.g. Fearnside et al. 2000). So-called ton-year approaches time-integrate the change in atmospheric CO_2 induced by a project implementation and are useful metrics to account for displaced emissions of CO_2 (Moura Costa and Wilson 2000). However, they do not take the emission and atmospheric dynamics of CH_4 into account, which would be important in the case of peatland rewetting.

Depending on the water table depth (WTD) and thus size of the GHG fluxes the time to reach negative radiative forcing will vary even for a successfully implemented project. Obtaining net cooling from rewetting may take more than one century (e.g. (Nugent et al. 2019) and thus goes beyond the chosen time horizon for carbon crediting of rewetting projects, which is often in the range of years or decades (Joosten et al. 2015; FAO 2020; IUCN 2023). Possible indicators for reaching net cooling thus need to be evaluated in order to contextualize rewetting success.

Furthermore peatlands hold carbon stocks of different size. Accordingly, the magnitude of avoidable emissions and the time horizon of sustained emissions in a baseline scenario without rewetting will vary. As a consequence, the achievable payment, or other incentives via policies for a project is site dependent not only in terms of the GHG fluxes, but also in terms of soil carbon stock.

Together, these questions call for improving our understanding of the climate effects of both, successful and temporary peatland rewetting in the context of carbon accounting and NBS. The goals of this study are threefold: 1) evaluating suitable indicators to assess the climate benefit of rewetting; 2) exploring the possible range of emission savings with permanent and non-permanent peatland rewetting over different time scales, and 3) analysing the role of different carbon stocks therein. Based on these considerations, an approach for biophysical discounting i.e. a discount metric based on the fate of the GHGs in the atmosphere and the radiative forcing they induce over time, is suggested.

2 Methodology

The CO_2 and CH_4 emissions from both drained and rewetted peatlands were simulated using the response of these emissions to WTD according to Tiemeyer et al. (2020) for CO_2 and Evans et al. (2021) for CH_4 (Supplementary Fig. S1). Although also Tiemeyer et al. (2020) provide a response function for CH_4, the function of Evans et al. (2021) extends to a water table of up to + 0.02 m, thereby allowing to analyse also the effect of very high water tables (inundation) on CH_4 fluxes. These functions are based on measurements at multiple sites in Europe and are taken here as representative for discussing the principal effects of rewetting on radiative forcing as well as the issue of non-permanence, acknowledging that the WTD-GHG relationship is always site-specific. It should be noted, that not only wet but also ditch-drained peatlands emit CH_4, which needs to be explicitly taken into account in measurement campaigns (e.g., Perryman et al. (2024). N_2O emissions are more difficult to address in the context of rewetting, as the relationship between WTD and N_2O is much less clear than for the other two GHGs. Koch et al. (2023) found no clear relationship between N_2O emissions and WTD. For grassland on organic soils in Germany Tiemeyer et al. (2016) observed higher emissions with intermediate WTD, while Tiemeyer et al. (2020), using a much larger data set from Germany, found no clear response of N_2O emissions to any of the available drivers. Even in the most comprehensive data set available to date, the WTD-N_2O relationship remains ambiguous, with fluxes on average highest at intermediate WTD (Lin et al. 2022). To explore the possible effect of changing N_2O emissions on the overall GHG balance with rewetting, in addition to those of CH_4 and CO_2, we computed two bins of the data in Lin et al. (2022), namely −0.55—0.65 m (drained), and −0.1 – 0.0 m (rewetted) (negative numbers denote water table below, positive numbers above the surface) and used the corresponding average N_2O fluxes (9.48 and 0.14 kg N_2O-N ha^{-1} yr^{-1}, respectively).

Tiemeyer et al. (2020) show that the formation of new peat only occurs when the WTD is at or above −0.08 m. Sites with net carbon accrual and high WTD in Tiemeyer et al. (2020) and Evans et al. (2021) were not under regular agricultural management, but were mostly covered with peatland vegetation (i.e., *Sphagnum spp*. for bogs, and sedges and reeds for fens). Therefore, in addition to a near-surface water table, the presence of specific peatland vegetation and avoidance of biomass removal typically supports carbon accrual when former peatland sites are rewetted, although harvested paludiculture sites (with, e.g., *Typha, Phragmites*) can also become net carbon sinks (Günther et al. 2015; Bianchi et al. 2021). Tiemeyer et al. (2020) indicate a maximum annual C-loss rate of a drained peatland of 10.0 t CO_2-C ha^{-1} at WTD > −0.60 m. In our study a WTD of −0.60 m below surface is taken as baseline scenario. WTD’s only up to + 0.02 m are considered. As simplification, carbon from CH_4 emission, which is mostly low but may reach up to 0.24 t CH_4-C ha^{-1} at flooding (Evans et al. 2021) is assumed to be not fuelled by the peat itself, but considered to stem mostly from labile plant litter (Escobar et al. 2022). This is relevant for calculating the remaining lifetime of the decomposing peat. With rewetting, CH_4 emissions are considered constant over time for a specific water table, following Wilson et al. (2016), who showed no significant difference in methane fluxes from natural and rewetted peatlands.

The radiative forcing (RF) [W m^{-2}] of the Earth system due to some imposed perturbation, such as anthropogenic GHGs, quantifies the energy imbalance that occurs when the imposed change takes place (Myhre et al. 2013). RF of the emissions and removals of both GHGs was calculated at annual time steps following the impulse response functions described in Myhre et al. (2013) using a radiative efficiency of 1.7049^{-15} W m^{-2} kg CO_2^{-1}. The latter represents the radiative forcing per unit change in concentration and was calculated from the radiative efficiency of CO_2 of 1.33×10^{-5} W ppb^{-1} (IPCC 2021) and a conversion to unit mass as provided by Myhre et al. (2013) based on an atmospheric mass of 5.1352×10^{18} kg. The temporal dynamics of atmospheric CO_2 following an emission into or a removal from the atmosphere is represented by four different reservoirs, a_i, contributing relative shares of 0.2173, 0.224, 0.2824 and 0.2763. Corresponding perturbation lifetimes τ_i of 10^6, 394.4, 36.54 and 4.304 years were used following Joos et al. (2013) and Millar et al. (2017).

$$RF = (\sum_{i=1}^{4} a_i \times e^{\left(\frac{-t}{\tau_i}\right)}) \times R_E \tag{1}$$

The RF is presented as absolute global warming potential AGWP [W m^{-2} yr], i.e. the cumulative forcing over time in sensu Joos et al. (2013).

$$AGWP = \int_0^H RF(t)dt \tag{2}$$

with H the time horizon of the integration [years].

Methane is represented by one single exponential decay function with perturbation lifetime of 12.4 years, using a radiative efficiency of 1.28×10^{-13} W m^{-2} kg^{-1} CH_4 and a multiplicator of 1.65 to account for indirect effects (Myhre et al. 2013). Nitrous oxide is also represented by one single exponential decay function with perturbation lifetime of 121 years, using a radiative efficiency of 3.83×10^{-13} W m^{-2} kg^{-1} N_2O and a multiplicator of 0.93 to account for indirect effects (Myhre et al. 2013).

All calculations are based on converting one hectare of land.

The atmospheric response to continued drainage of a peatland (i.e., baseline scenario) to −0.60 m is compared with the scenario of successful rewetting and scenarios where rewetting is stopped and followed by drainage 10 – 90 years after rewetting initiation, resulting in different periods of wet and dry peatland. The balance of CH_4 vs. CO_2 as well as N_2O emissions over time are further influenced by the available peat carbon stock, itself determined by peat thickness, soil bulk density and carbon concentration, because drained peatlands are net CO_2 emitters only as long as they store peat. Peat carbon stocks vary widely depending on the type of peatland ecosystem and state of degradation. Based on the recent Global Peatland Assessment (UNEP 2022), a range of 500 to 1500 t C ha^{-1} is used here to illustrate how the benefit of rewetting relative to the baseline is linked to the amount of carbon available for decomposition, i.e. to a possible exhaustion of the peat deposit during the project. This carbon stock corresponds, depending on soil bulk density and carbon concentration, to peat thicknesses of approximately 0.8 – 2.1 m (UNEP 2022).

In accordance with Fig. S1, rewetting results in an increase in soil carbon storage during periods of high water table (provided that peat-forming vegetation is present and anthropogenic disturbances such as fires are absent). Carbon sequestered during that time is considered to add to the available peat deposit and the CO_2 emitted after draining a rewetted site. N_2O emissions also depend on the amount of peat present, as most N_2O from managed peatlands stems from peat decomposition rather than fertilisation (Wang et al. 2024). Accordingly, we used the N_2O emissions for drained states from Lin et al. (2022) only as long as peat is present, and replaced it with the average emission for fertiliser-induced N_2O emissions (2.22 kg N_2O-N ha^{-1} yr^{-1}) from drained organic cropland soils as reported by Wang et al. (2024).

Switchover time is the length of time after which the positive radiative forcing due to increases in CH_4 emissions at a restored peatland is overtaken by the cumulative negative radiative forcing due to CO_2 uptake (Hemes et al. 2019). In other words, a net cooling effect, i.e. a climate benefit not only relative to a business as usual but also in absolute terms, is only accomplished via net C uptake, i.e., peat growth. This is an important consideration as for many situations with an increase in the water table, an improvement relative to the baseline scenario is achieved, but the new system remains climate negative, i.e., warming. In this study, the cumulative (Eq. 2) as well as the instantaneous RF (Eq. 1) will be used to calculate switchover times and to derive an optimum WTD range. Furthermore, the optimum WTD is calculated using the AGWP after 100 and 500 years.

To allow a direct comparison of the different scenarios, it was assumed that CH_4 emission begins with the start of the simulation and that no atmospheric equilibrium at t0 occurs.

3 Results

3.1 Radiative forcing of drained and rewetted peatland over time

The cumulative radiative forcing (AGWP, Eq. 2) strongly depends on WTD as shown for four different WTDs over 500 years for a peat deposit of 1000 t C (Fig. 1). The four depths were chosen to represent maximum CO_2 release (−0.60 m) and the sensitive zone where the system switches from a CO_2 source to a CO_2 sink and increased CH_4 source strength. A WTD of −0.60 m induces a warming, i.e. cumulative forcing, of 1060 nW m^{-2} ha^{-1}, which is reduced to 883 nW m^{-2} ha^{-1} at WTD of −0.15 m. At WTD of −0.05 m, peat is formed and the AGWP becomes negative (−35 nW m^{-2} ha^{-1} after 500 years). With inundation (+0.02 m), the rewetted peatland remains climate negative (i.e., warming) over the whole period. The radiative forcing is dominated by CO_2 at deep water tables, whereas both gases contribute approximately the same but with opposite signs (i.e. cooling for CO_2, warming for CH_4) when the WTD is closely below or above the surface (Supplementary Figure S2). The analysis of cumulative forcing across

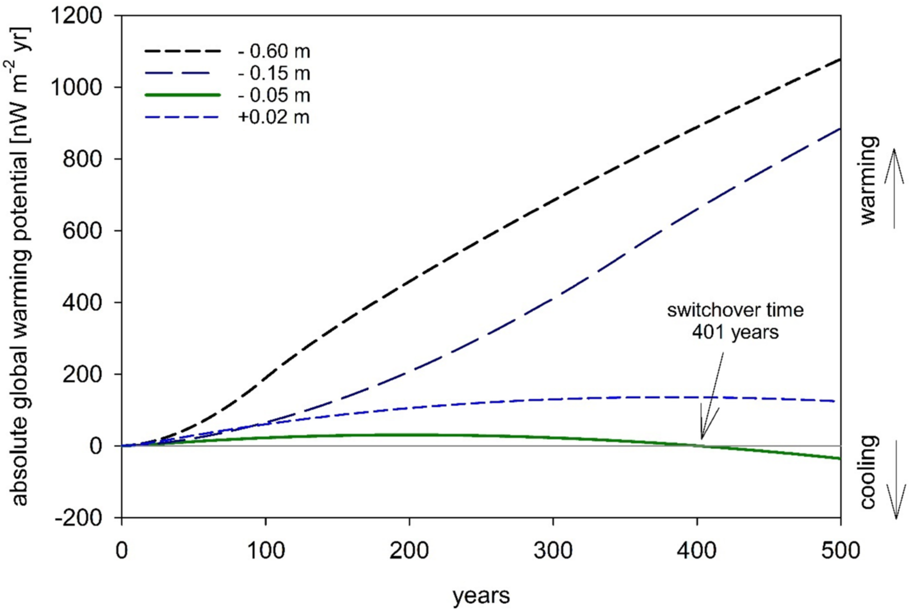

Fig. 1 Cumulative radiative forcing (AGWP) through time for converting one hectare of land for four WTD's, calculated for a peat deposit of 1000 t C and GHG emission rates following Figure S1. GHGs considered: CO_2 and CH_4

different water levels reveals a minimum at −0.06 m WTD for a time horizon of 100 years of drainage, and −0.04 m for 500 years (Fig. 2).

Within the range of WTDs that allow peat built-up, switchover times for the cumulative radiative forcing are between 398 and 1846 years, and the minimum of 398 years is reached at WTD of −0.04 m (Fig. 3). Only for WTDs of between −0.08 and + 0.02 m (the maximum WTD considered in this study) can a net climate cooling be obtained. When not the cumulative, but the instantaneous radiative forcing RF (eq. [1]) is followed, switchover times are shorter. The instantaneous RF reflects the effect of the contemporary GHG content in the atmosphere. The corresponding curve for the calculations in this study, dashed in Fig. 3, is overall indicating shorter switchover and reaches its minimum of 201 years at −0.04 m WTD. This means that from 201 years onwards the rewetted peatland ecosystem with a WTD of −0.04 m is cooling. The switchover time for the same scenario but calculated with the cumulative forcing considers the memory effect of contributions to warming in the first two centuries after rewetting, where CO_2 uptake does not (yet) outweigh CH_4 release. As described in the methods section, the response of N_2O to WTD is less clear than for CO_2 and CH_4. Assuming that a rewetted peatland at −0.04 m emits 0.14 kg N_2O-N ha^{-1} yr^{-1} (Lin et al. 2022), switchover times for cumulative and instantaneous forcing become slightly longer, 406 and 205 years respectively.

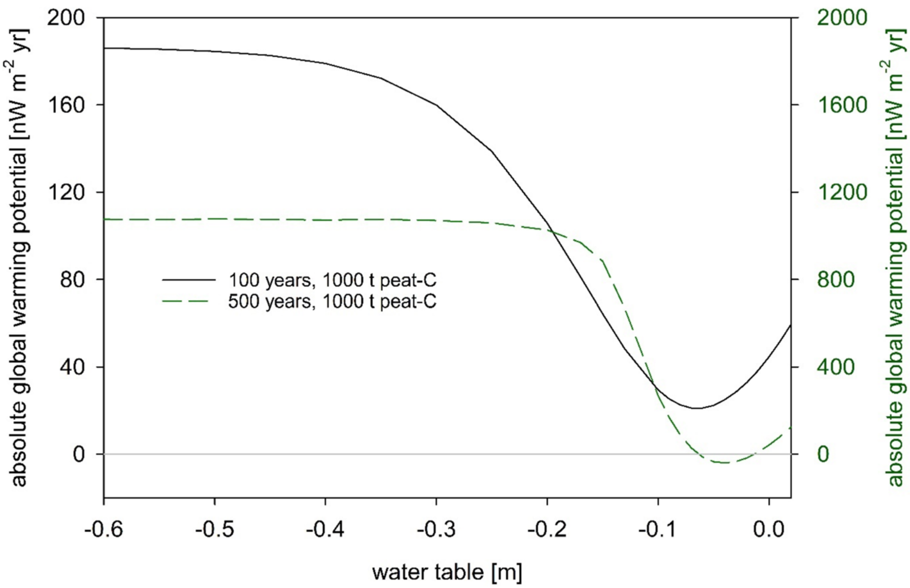

Fig. 2 Cumulative radiative forcing (AGWP) for converting one hectare of land along a gradient of WTD of −0.60 to + 0.02 m for a peat deposit of 1000 t C. Black: Calculated over 100 years (left y-axis), green: calculated over 500 years (right y-axis). Note that the black line is always in the positive region, i.e., net cooling cannot be achieved with any water table during the first 100 years of rewetting. In contrast, the green line has a negative AGWP for high WTD's, i.e. switchover is obtained following 500 years of rewetting with high WTD of between −0.06 and −0.02m. Solid grey line represents zero warming for both time horizons. GHGs considered: CO_2 and CH_4

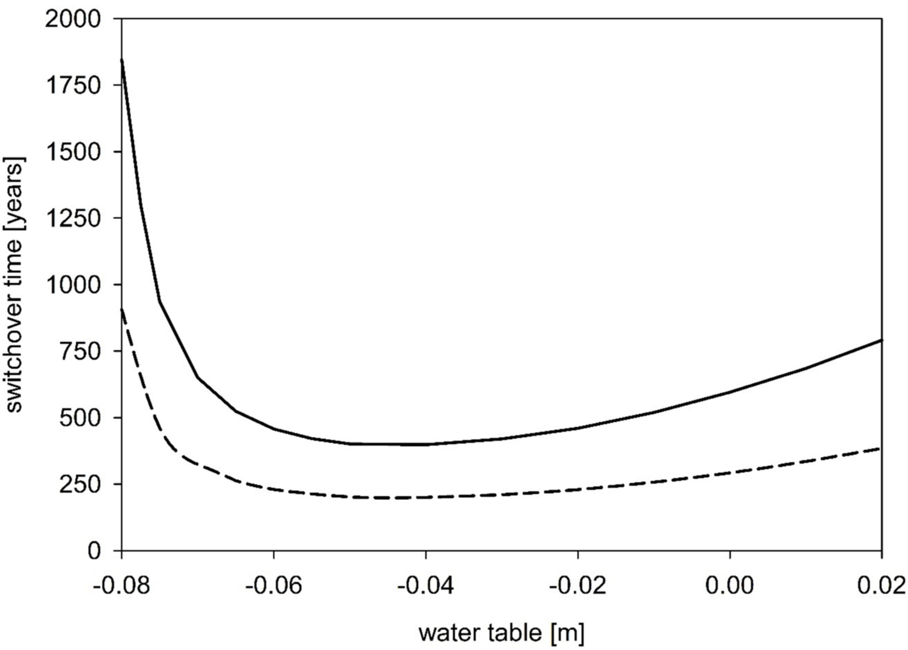

Fig. 3 Switchover times along a water table gradient for rewetting managed organic soils using the cumulative (solid line), and the instantaneous radiative forcing (dashed line). Emissions of CO_2 and CH_4 follow the functions in Fig. S1. For water table depths below −0.08 m no switchover occurs and the climate effect remains negative because of no net C accrual. GHGs considered: CO_2 and CH_4

3.2 Effects of different peatland carbon stocks

The GHG flux of the baseline scenario (WTD −0.60 m) is dominated by the emitted CO_2 from peat decomposition. If the peat is fully decomposed during the projected time line (e.g., after 100 years in case of a 1000 t SOC deposit and a loss rate of 10 t CO_2-C ha^{-1} yr^{-1}), it will no longer contribute to CO_2 emissions whereas CH_4 emissions continue, hence the advantage of rewetting becomes smaller. This is illustrated for a range of peat carbon stocks in Fig. 4. With deep drainage (−0.60 m, annual CO_2 emission factor 10 t CO_2-C ha^{-1}), the forcing cumulated over 100 years increases from 134 to 186 nW m^{-2} ha^{-1} with the C stock increasing from 500 to 1500 t. Cumulated over 500 years, the forcing is 567 nW m^{-2} for a C stock of 500 t but becomes 1539 nW m^{-2} when 1500 t ha^{-1} peat carbon are available. The increase is strongly non-linear when calculated over 100 years owing to the exhaustion of the peat if less than 1000 t C are stored. Also for integrating over 500 years the increase is slightly non-linear but only owing to the equilibration of atmospheric CH_4-concentrations during the first decades. For a water table of −0.05 m (annual peat accrual 0.71 t C ha^{-1}; see. Fig. S1), the cumulative forcing becomes 22.3 and −35.1 nW m^{-2} for rewetting one ha of land over 100 and 500 years, respectively, and is independent of the peatland C.

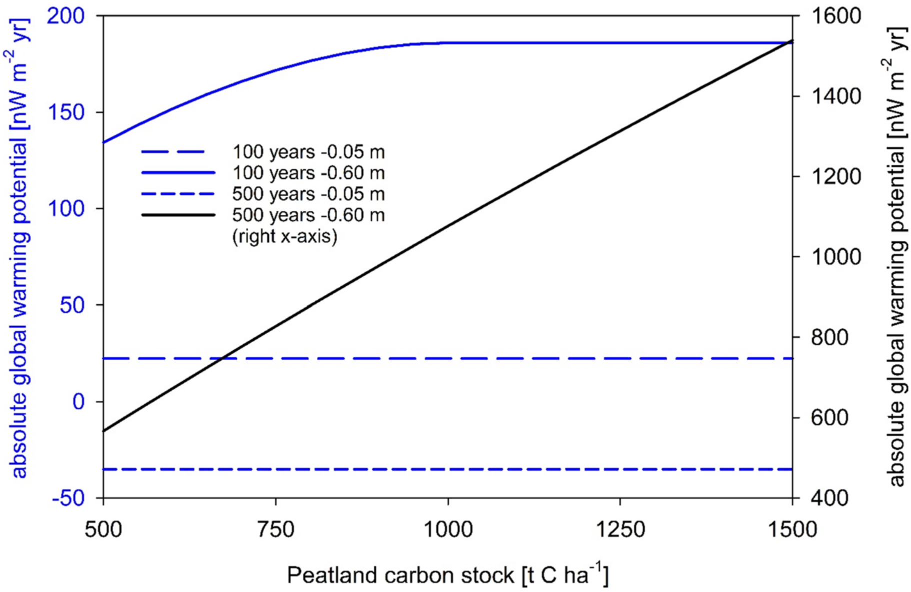

Fig. 4 Cumulative radiative forcing (AGWP) for converting one hectare of land along a gradient of peatland carbon stocks for two different WTD's and for two different time horizons. Please note right Y-scale which gives the forcing for 500 years −0.60 m, whereas left Y-scale gives the forcing for all other combinations. GHG considered: CO_2 and CH_4

3.3 Reversibility of peatland rewetting

Assuming a constant CO_2 emission factor with drainage, the avoided peat C loss over one century is linearly related to the number of years of successful rewetting (Fig. 5). Hence, with an overall potential of losing 1000 t CO_2-C, half of it will be lost, at an annual rate 10 t C ha^{-1}, when the project area was successfully rewetted for only 50 years. If not only soil-C is considered, but the fate of both CO_2 and CH_4 over time by using RF calculations, the relationship is curved: Only 30 years of successful rewetting avoids 50% of the warming as would be induced by continuous drainage for 100 years. With 50 years of rewetting the saving becomes approximately 74% of the maximum climate benefit (9.4 and 18.1% for 5 and 10 years, respectively). A detailed view on the atmospheric CO_2-Ceq. over 100 years for different durations of successful rewetting is provided in Supplementary Fig. S3. Furthermore, the shape of the relationship between the duration of successful rewetting and avoided warming (blue curve in Fig. 5) is insensitive to the project duration: For a partial rewetting success relative to project durations of 30, 50, and 70 years, the percent avoided warming is similar and well described by a second order polynomial (Supplementary Fig. S4). This relationship holds true as long as interrupted or reversed rewetting does not exhaust the SOC pool.

Evaluating the atmospheric effect of different rewetting successes that take place over the first century but over much longer time scales gives a different picture: Over centuries, the atmospheric GHG load from all scenarios except for permanent rewetting will converge (Fig. 6). The convergence occurs because of the finite size of any peat deposit which implies a decrease of CO_2 in the atmosphere after exhaustion of the source. This

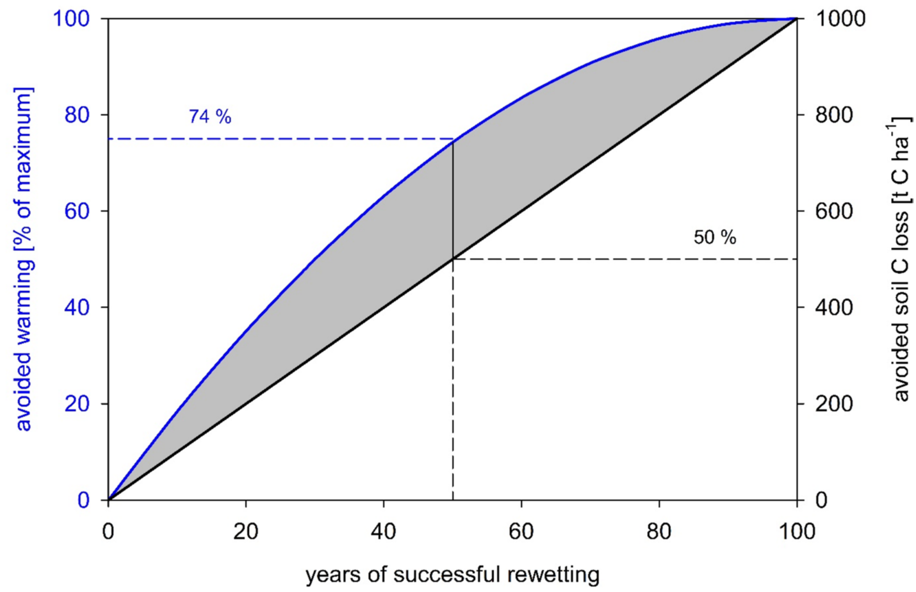

Fig. 5 Avoided soil C loss and avoided warming at WTD −0.05 m relative to WTD −0.60 m over 100 years as a function of rewetting success. The grey area represents the difference when interpreting rewetting success based on the radiative forcing (blue) as compared to the soil C-stock only (black). Explicit numbers for avoided warming (%) are discussed in the text. Reading example: If only the first five decades were successfully rewetted and the systems falls thereafter dry again, 74% of the warming avoided over one century of successful rewetting is achieved. GHG considered: CO_2 and CH_4

means that temporary rewetting represents a displaced emission without climate benefit in the long run. Table S1 details the corresponding difference in cumulative forcing. Whereas over 100 years of computation the duration of successful rewetting in the first century makes a difference, the benefit diminishes over 500 and 1000 years because of the onset of CO_2 emission after water table drawdown until the peat deposit is fully oxidized.

4 Discussion

4.1 Managing rewetting: switchover times and peatland carbon stock

We analysed three possible indicators for obtaining the optimum WTD for successful peatland rewetting in terms of climate cooling. These are switchover times [yr], calculated based either on cumulative or on instantaneous radiative forcing, and the cumulative forcing [W m^{-2} yr] itself. Differences between switchover times either using the instantaneous or the cumulative forcing are substantial, but the corresponding optimum WTD of −0.05 m is the same. The cumulative RF also shows optimum WTD's of between −0.04 and −0.06 m, depending on the integration period. As N_2O emissions from rewetted sites are typically very low, including N_2O only adds a few years to the switchover times. Together, differences between the derived values are very small and imply that any of these indicators is suitable to obtain the optimum WTD which is needed to inform project managers or

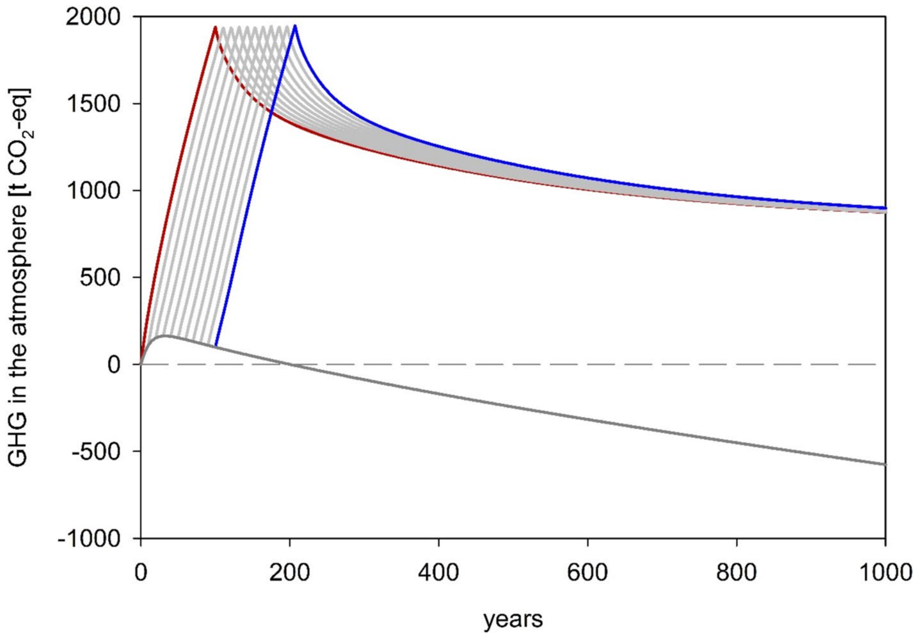

Fig. 6 GHG content in the atmosphere for different periods of rewetting one ha peatland with 1000 t C to WTD of −0.05 m during the first century and conversion to full drainage (WTD of −0.60 m) between t10 and t100. Data are the same as Fig. S3 but calculated over one millennium. Lines for 0 years (red, i.e., no rewetting) and 100 years (blue) of successful rewetting are coloured to improve visibility. Lower solid grey line indicates permanent rewetting assuming no change in annual net C uptake of the system over one millennium. CO_2-equivalents were calculated from the forcing induced by CO_2 plus CH_4 by back-calculation using the corresponding radiative efficiency of CO_2. Please note that the notion for CO_2-equivalents used here is not equal to the commonly used GWP_{100}. GHGs considered: CO_2 and CH_4

decision makers. We recall, however, that the optimum WTD might be site-specific as it is highly dependent on net C accrual as well as on CH_4 emission rates after rewetting which are notoriously variable (Mander et al. 2023) and difficult to predict (Antonijević et al. 2023). Furthermore, our calculations are based on generic curves derived from GHG flux measurements mainly from the temperate zone and switchover times in the tropics may differ from those derived here as consequence of often much lower CH_4 emissions in tropical peatlands (Couwenberg et al. 2010; IPCC 2014). For example, Ojanen and Minkkinen (2020) showed a faster onset of cooling by rewetting in the tropics than in the temperate and boreal zones and Dommain et al. (2018) showed shorter switchover times for tropical peatlands compared to a boreal site when simulating natural peatland growth. However, a strong dependence of CO_2 from peat oxidation on WTD has also been found for tropical peatlands (Couwenberg et al. 2010; Novita et al. 2024) and the principle of calculation as presented in our approach would therefore remain the same.

Calculated switchover times revealed that only for WTD's of between −0.08 m and + 0.02 m can a net climate cooling be obtained from peatland rewetting, as this requires a net sink for carbon and no net sink is achieved with WTD below this. In other words, WTD's below −0.08 m may reduce GHG emissions and thus provide a climate benefit from reduced peat decomposition relative to deep drainage, but do not convert the system to a net cooling one using the generic functions in Fig. S1.

Switchover times indicate the time needed to achieve net climate cooling. Based on Fig. 3 they are in the order of centuries, depending on water table and whether they were calculated for instantaneous or cumulative forcing. Although both approaches are valid and used in the literature, it is important to recognize that the integrative indicator, which reveals longer switchover times, considers the memory effect of past CO_2 and CH_4 fluxes since onset of a project.

For rewetted peatlands in California under Mediterranean climate, observed switchover times calculated using cumulative forcing were 101 and 142 years for the conversion from corn and pasture, respectively (Hemes et al. 2019). These relatively short switchover times were caused by the much higher C uptake of these ecosystems compared to the net uptake at high WTD of temperate sites as used in this study (Tiemeyer et al. 2020). Switchover times have also been calculated using the instantaneous but not the cumulative RF (Frolking et al. 2006; Frolking and Roulet 2007). Northern peatlands become net cooling centuries to millennia after onset of peat formation. In this context, a higher ratio of CH_4 release to CO_2 uptake induces a longer switchover time (Frolking et al. 2006). For restoring peat extraction sites in Canada, Nugent et al. (2019) calculated instantaneous switchover times of 180 years, which is very close to the minimum of 201 years in our estimates (Fig. 3, WTD −0.04 m). Switchover times as calculated here are far beyond the time horizon of 100 years as for example required for project durations by the Voluntary Carbon Standard for peatland areas to be eligible for carbon crediting (VCS 2017). Although the latter is based on crediting against a baseline, i.e. selling an emission saving, it should be emphasised that even if a rewetting project is deemed successful in the context of carbon farming schemes and provides a climate benefit it will still contribute to global warming over the time horizon of the certification or related policy and beyond.

The size of the peatland C stock protected by rewetting from aerobic decomposition becomes particularly relevant for the magnitude of the climate benefit in the long-run. Whereas the RF of rewetting a site is not sensitive to the initial amount of peat, the time until exhaustion of the peat deposit with deep drainage, i.e. the baseline, depends on the peatland C stock. It is expected to occur within decades to centuries considering the loss rate of 10 t C ha^{-1} yr^{-1}. Over 100 years, a drained 500 t C stock induces an AGWP of 134 nW m^{-2} ha^{-1}, whereas this value rises to 186 nW m^{-2} ha^{-1} with 1500 t C. This difference is more pronounced over 500 years (567 vs. 1539 nW m^{-2} ha^{-1}) (Fig. 4), because AGWP presents the cumulative forcing, which is dominated by the long-lived CO_2 and hence also reflects the emission history. Differences in initial C stocks are therefore almost always relevant and rewetting C rich peatlands gives a greater climate benefit via emission savings. Importantly, the warming induced by draining C rich peatlands become fully effective over many centuries, underpinning that rewetting those sites should have highest priority. The calculations presented assume constant annual CO_2 loss from peatland drainage until the peat deposit is exhausted. If CO_2 emission factors are higher at the onset of drainage and decline thereafter, the same magnitude of forcing would occur earlier in time (Leifeld and Lupascu 2023).

4.2 Climate benefits of permanent and non-permanent rewetting and biophysical discounting

Using similar approaches of combining impulse response functions and radiative efficiencies, benefits of permanent rewetting were described previously. Günther et al. (2020) showed that the instantaneous rewetting of all drained peatland worldwide would result in a RF less than half of that of a baseline without any rewetting by end of this century. Also Ojanen and Minkkinen (2020) derived an immediate positive effect for rewetting, relative to drainage, for agricultural soils in the tropics. The positive effect was delayed in temperate and boreal zones owing to the higher ratio of CH_4 emitted with rewetting to CO_2 saved. These authors also pointed out that rewetting of temperate and boreal forest sites was not always climate positive in the early decades, not only because of increased CH_4 emissions, but also because of reduced carbon storage in trees and wood products, which further delayed the onset of the cooling effect. Together, these studies indicated a strong beneficial effect of rewetting relative to the baseline on RF but also identified transient times where rewetting still contributes to climate warming, in line with the findings of this study. The dynamics of RF after rewetting may further be modulated by three other factors, namely plant productivity, albedo, and peat growth. Plant productivity and thus CO_2 uptake after onset of a project may change over time in relation to plant growth and vegetation succession (Nugent et al. 2019). Vegetation changes not only affect the earth's climate via changing GHG fluxes, but also via altered albedo (Portmann et al. 2022). In the case of peatland afforestation, albedo changes may substantially reduce the RF benefit from carbon uptake (Lohila et al. 2010). Consequently, both vegetation development and albedo should be monitored in order to quantify the overall climate effect of rewetting projects. Globally peat accumulation has occurred over millennia and is still ongoing in undisturbed peatlands (Yu et al. 2010), but growth rates may vary over time and even decrease in the long term depending on future environmental conditions (Gallego-Sala et al. 2018). Therefore, the scenario of successful rewetting over 1000 years shown in Fig. 6, based on contemporary flux measurements, is not considered a universal projection of future peat growth, but one realistic pathway.

Project payments in rewetting or carbon sequestration projects are often realized upfront, i.e. ex-ante, and uncertainties in project performance are addressed by buffer accounts or mixing project portfolios of different focus (COWI et al. 2021). Such approaches do not explicitly account for the temporary, i.e. time value of carbon storage or emission reduction (Murray et al. 2007; Leifeld 2023). In this paper we support ex-ante discounting but using the nonlinear relationship provided in Figs. 5 and S4. We call this biophysical discounting. Such an approach is not sensitive to the integrated time horizon, making it appropriate for different project durations. It can be combined with payment by instalments, e.g. on an annual basis. Following Fig. 5, a project designed for e.g. 100 years would pay the owner 9.4% of the total after 5% of the project's lifetime (i.e. 5 years), years, 9.1% after the following 5 years etc. The same discount, relative to the project duration, applies to shorter and longer project durations (e.g., 9.4% of the total after 2.5 years for a project duration of 50 years) (Fig. S4). The approach thus offers the benefit for the investor of paying only for accomplished climate benefits within the project's timeframe. It can be combined with already existing economic approaches for valuing temporary credits in monetary terms (Murray et al. 2007; Marshall and Kelly 2010). Biophysical discounting may also help to simplify the currently complex landscape of certification and standards for CO_2 removals (Arcusa and Sprenkle-Hyppolite 2022). Overall, biophysical discounting is a suitable approach to clearly account for the duration of the climate benefit and distinguish permanent from temporary measures as called for by e.g. the policy of the European Commission (EC 2022b).

The approach as presented here is also applicable to account for possible project failures if a specified period, in our example 100 years is deemed equivalent to 'permanent' as suggested in corresponding schemes (Joosten et al. 2015; VCS 2017). Yet, under the condition of a fixed time horizon, the contribution of a non-permanent rewetting relative to a successful rewetting over the same time horizon can be quantified. However, while biophysical accounting is a useful approach for linking payments to the temporal success of a measure, it does not solve the general obstacle associated with non-permanence in the time-course of centuries. We show that over time, the atmospheric GHG load from only temporary rewetting will converge and long-term net cooling is only achieved via permanent rewetting. The convergence occurs because of the finite size of any peat deposit which implies a decrease of CO_2 in the atmosphere after exhaustion of the source. This means that temporary rewetting represents a displaced emission without climate benefit in the long run. This raises the question whether permanence over one century is worth the same as permanence for longer times? The European Commission (EC 2022b) suggested to limit the validity of the certified carbon removals subject to an expiry date that matches with the end of the relevant monitoring period, after which the carbon should be assumed to be released into the atmosphere. However, a methodological framework for implementation has not been presented yet. Our study shows that in case of an unsuccessful long-term increase of the water table and reversal of the situation to high CO_2 release beyond a project timeline of e.g. one century, a rewetting project represents a displaced GHG emission, and therefore merely a GHG saving for a limited period. For such a limited period, biophysical discounting as suggested above might apply.

Displacing emissions by a few decades allows us to buy time by moving the climate burden further into the future, but has no climate benefit when the time horizon is extended far beyond 100 years (Leifeld 2023). In contrast to this, both temporary and permanent biological carbon sequestration, i.e. the net uptake of atmospheric CO_2 by the ecosystem and built-up of a carbon sink, always offer a positive (i.e. cooling) effect on the climate which is quantifiable over any time frame (Sierra et al. 2021; Leifeld and Keel 2022). It has therefore been argued that, from a biophysical viewpoint, non-permanence of carbon sinks does not constitute a knock-out criterion for NBS and carbon markets (Leifeld 2023). Unlike in carbon sink projects, a possible failure of peatland rewetting projects will not be a climate benefit in the long term (Fig. 6) as stated previously (Bonn et al. 2014), but rather just temporarily reduce and postpone emissions (see Fig. S3). Our finding is also in contrast to IUCN (2023), who stated that the emissions reductions that are achieved before reversal to low water tables remain permanent as well as in contrast to Joosten et al. (2015), who argue that in the case of avoided emissions in a peatland rewetting project, project reversal does not lead to a nullification of the positive effects. Rather, we show that unsuccessful long-term rewetting eliminates the temporary climate relief achieved in the beginning.

5 Conclusion

The creditability of carbon farming schemes both in the private and the public sector has been scrutinized (e.g., West et al. 2020; Popkin 2023), and trustworthiness will remain crucial if NBS via carbon farming shall play a significant role in mitigating climate change. Carbon farming practices in mineral soils come with obstacles such as organic matter stoichiometry constraints, biomass availability, off-site emissions, and small per-area potentials (Schlesinger 2022). Peatland rewetting provides benefits in terms of high mitigation potentials per hectare, no additional nutrient requirement (Leifeld and Menichetti 2018), and by providing other valuable ecosystem services (Grand-Clement et al. 2013).

One obstacle to financial compensation for peatland rewetting has been how to deal with possible project failures. In this paper we show that valuating the climate benefit of peatland rewetting is best achieved via biophysical discounting, i.e. a discount metric based on the fate of the GHGs in the atmosphere and the radiative forcing they induce over time. Biophysical discounting can inform and guide payments within NBS schemes and, furthermore, provides flexibility in addressing emission savings over different time horizons and in evaluating the role of variable carbon stocks. Yet possible project failure and its impact on the climate needs to be clearly and verifiably addressed in carbon farming schemes for peatland rewetting, which is lacking hitherto.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11027-025-10203-2.

Author contribution J.L. conceptualized the research, carried out the simulations and wrote the original draft. C.W-G. and S.M.P. contributed to literature review and analysis. C. W-G. edited the language. All co-authors reviewed, commented and edited the original draft. All authors read and approved the final manuscript.

Funding Open access funding provided by Agroscope No funding was received for this study.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration

Competing interests The authors declare no competing interests for this study.

References

Allen MR, Shine KP, Fuglestvedt JS, Millar RJ, Cain M, Frame DJ, Macey AH (2018) A solution to the misrepresentations of co2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. npj Clim Atmos Sci 1(1):16. https://doi.org/10.1038/s41612-018-0026-8

Antonijević D, Hoffmann M, Prochnow A, Krabbe K, Weituschat M, Couwenberg J, Ehlert S, Zak D, Augustin J (2023) The unexpected long period of elevated ch4 emissions from an inundated fen meadow ended only with the occurrence of cattail (typha latifolia). Glob Change Biol 29(13):3678–3691. https://doi.org/10.1111/gcb.16713

Arcusa S, Sprenkle-Hyppolite S (2022) Snapshot of the carbon dioxide removal certification and standards ecosystem (2021–2022). Climate Policy 22(9–10):1319–1332. https://doi.org/10.1080/14693062.2022.2094308

Bianchi A, Larmola T, Kekkonen H, Saarnio S, Lång K (2021) Review of greenhouse gas emissions from rewetted agricultural soils. Wetlands 41(8):108. https://doi.org/10.1007/s13157-021-01507-5

Bonn A, Reed MS, Evans CD, Joosten H, Bain C, Farmer J, Emmer I, Couwenberg J, Moxey A, Artz R, Tanneberger F, von Unger M, Smyth M-A, Birnie D (2014) Investing in nature: developing ecosystem service markets for peatland restoration. Ecosyst Serv 9:54–65

Couwenberg J, Dommain R, Joosten H (2010) Greenhouse gas fluxes from tropical peatlands in south-east asia. Global Change Biol 16(6):1715–1732. https://doi.org/10.1111/j.1365-2486.2009.02016.x

COWI, Ecololgic Institute and IEEP (2021) Technical guidance handbook - setting up and implementing result-based carbon farming mechanisms in the EU Report to the European Commission, DG Climate

Action, under Contract No. CLIMA/C.3/ETU/2018/007. COWI, Kongens Lyngby. Available at https://data.europa.eu/doi/10.2834/12087
Darusman T, Murdiyarso D, Impron & Anas I (2023). Effect of rewetting degraded peatlands on carbon fluxes: a meta-analysis. Mitig Adapt Strateg Glob Chang 28(3) 10. https://doi.org/10.1007/s11027-023-10046-9
Dommain R, Frolking S, Jeltsch-Thömmes A, Joos F, Couwenberg J, Glaser PH (2018) A radiative forcing analysis of tropical peatlands before and after their conversion to agricultural plantations. Glob Change Biol 24(11):5518–5533. https://doi.org/10.1111/gcb.14400
EC (2021) Communication from the commission to the european parliament and the council: sustainable carbon cycles. Com(2021) 800, Document 52021DC0800. European Commission, Brussels
EC (2022a) Proposal for a regulation of the european parliament and of the council establishing a union certification framework for carbon removals. 2022/0394 (cod), Document 52022PC0672. European Commission, Brussels
EC (2022b) Impact assessment report accompanying the document: proposal for a regulation of the europan parliament and of the council establishing a union certification framework for carbon removals. Com(2022) 672, Document 52022SC0377. European Commission, Brussels
Escobar D, Belyazid S, Manzoni S (2022) Back to the future: Restoring northern drained forested peatlands for climate change mitigation. Front Environ Sci 10:834371. https://doi.org/10.3389/fenvs.2022.834371
Evans CD, Peacock M, Baird AJ, Artz RRE, Burden A, Callaghan N, Chapman PJ, Cooper HM, Coyle M, Craig E, Cumming A, Dixon S, Gauci V, Grayson RP, Helfter C, Heppell CM, Holden J, Jones DL, Kaduk J, Levy P, Matthews R, McNamara NP, Misselbrook T, Oakley S, Page SE, Rayment M, Ridley LM, Stanley KM, Williamson JL, Worrall F, Morrison R (2021) Overriding water table control on managed peatland greenhouse gas emissions. Nature 593(7860):548–552. https://doi.org/10.1038/s41586-021-03523-1
FAO (2020) A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes – gsoc-mrv protocol. Rome. https://doi.org/10.4060/cb0509en
Fearnside PM, Lashof DA, Moura-Costa P (2000) Accounting for time in mitigating global warming through land-use change and forestry. Mitig Adapt Strat Glob Change 5(3):239–270. https://doi.org/10.1023/A:1009625122628
Freeman BWJ, Evans CD, Musarika S, Morrison R, Newman TR, Page SE, Wiggs GFS, Bell NGA, Styles D, Wen Y, Chadwick DR, Jones DL (2022) Responsible agriculture must adapt to the wetland character of mid-latitude peatlands. Glob Change Biol 28(12):3795–3811. https://doi.org/10.1111/gcb.16152
Frolking S, Roulet NT (2007) Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. Glob Change Biol 13(5):1079–1088. https://doi.org/10.1111/j.1365-2486.2007.01339.x
Frolking S, Roulet N, Fuglestvedt J (2006) How northern peatlands influence the earth's radiative budget: sustained methane emission versus sustained carbon sequestration. J Geophys Res: Biogeosciences 111(G1). https://doi.org/10.1029/2005JG000091
Gallego-Sala AV, Charman DJ, Brewer S, Page SE, Prentice IC, Friedlingstein P, Moreton S, Amesbury MJ, Beilman DW, Björck S, Blyakharchuk T, Bochicchio C, Booth RK, Bunbury J, Camill P, Carless D, Chimner RA, Clifford M, Cressey E, Courtney-Mustaphi C, De Vleeschouwer F, de Jong R, Fialkiewicz-Koziel B, Finkelstein SA, Garneau M, Githumbi E, Hribjlan J, Holmquist J, Hughes PDM, Jones C, Jones MC, Karofeld E, Klein ES, Kokfelt U, Korhola A, Lacourse T, Le Roux G, Lamentowicz M, Large D, Lavoie M, Loisel J, Mackay H, MacDonald GM, Makila M, Magnan G, Marchant R, Marcisz K, Martínez Cortizas A, Massa C, Mathijssen P, Mauquoy D, Mighall T, Mitchell FJG, Moss P, Nichols J, Oksanen PO, Orme L, Packalen MS, Robinson S, Roland TP, Sanderson NK, Sannel ABK, Silva-Sánchez N, Steinberg N, Swindles GT, Turner TE, Uglow J, Väliranta M, van Bellen S, van der Linden M, van Geel B, Wang G, Yu Z, Zaragoza-Castells J, Zhao Y (2018) Latitudinal limits to the predicted increase of the peatland carbon sink with warming. Nat Clim Chang 8(10):907–913. https://doi.org/10.1038/s41558-018-0271-1
Glenk K, Faccioli M, Martin-Ortega J, Schulze C, Potts J (2021) The opportunity cost of delaying climate action: Peatland restoration and resilience to climate change. Glob Environ Chang 70:102323. https://doi.org/10.1016/j.gloenvcha.2021.102323
Grand-Clement E, Anderson K, Smith D, Luscombe D, Gatis N, Ross M, Brazier RE (2013) Evaluating ecosystem goods and services after restoration of marginal upland peatlands in south-west england. J Appl Ecol 50(2):324–334. https://doi.org/10.1111/1365-2664.12039
Günther A, Huth V, Jurasinski G, Glatzel S (2015) The effect of biomass harvesting on greenhouse gas emissions from a rewetted temperate fen. GCB Bioenergy 7(5):1092–1106. https://doi.org/10.1111/gcbb.12214

Günther A, Barthelmes A, Huth V, Joosten H, Jurasinski G, Koebsch F, Couwenberg J (2020) Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat Commun 11(1):1644. https://doi.org/10.1038/s41467-020-15499-z

Hemes KS, Chamberlain SD, Eichelmann E, Anthony T, Valach A, Kasak K, Szutu D, Verfaillie J, Silver WL, Baldocchi DD (2019) Assessing the carbon and climate benefit of restoring degraded agricultural peat soils to managed wetlands. Agric for Meteorol 268:202–214. https://doi.org/10.1016/j.agrformet.2019.01.017

Huang Y, Ciais P, Luo Y, Zhu D, Wang Y, Qiu C, Goll DS, Guenet B, Makowski D, De Graaf I, Leifeld J, Kwon MJ, Hu J, Qu L (2021) Tradeoff of co2 and ch4 emissions from global peatlands under water-table drawdown. Nat Clim Chang. https://doi.org/10.1038/s41558-021-01059-w

IPCC (2014) 2013 supplement to the 2006 ipcc guidelines for national greenhouse gas inventories: wetlands. In: Hiraishi T, Krug T, Tanabe K. Srivastava N, Baasansuren J, Fukuda M, Troxler TG (eds). Switzerland, p 354

IPCC (2021) Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Channe Y, Goldfarb N, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 3−32. https://doi.org/10.1017/9781009157896.001

IUCN (2023) Peatland code guidance version 2.0. In: Peatland Programme, The National Trust for Scotland 2023 as nominee for the UK National Committee of the IUCN (ed). Newark, p 17. Available at https://www.iucn-ukpeatlandprogramme.org/

Joos F, Roth R, Fuglestvedt JS, Peters GP, Enting IG, von Bloh W, Brovkin V, Burke EJ, Eby M, Edwards NR, Friedrich T, Frölicher TL, Halloran PR, Holden PB, Jones C, Kleinen T, Mackenzie FT, Matsumoto K, Meinshausen M, Plattner GK, Reisinger A, Segschneider J, Shaffer G, Steinacher M, Strassmann K, Tanaka K, Timmermann A, Weaver AJ (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos Chem Phys 13(5):2793–2825. https://doi.org/10.5194/acp-13-2793-2013

Joosten H, Brust K, Couwenberg J, Gerner A, Holsten B, Permien T, Schäfer A, Tanneberger F, Trepel M, Wahren A (2015) Moorfutures. Integration of additional ecosystem services (including biodiversity) into carbon credits - standard, methodology and transferability to other regions. In: BfN-Skripten, F. A. f. N. Conservation (ed). Federal agency for nature conservation, p 119. Available at https://www.bfn.de/

Koch J, Elsgaard L, Greve MH, Gyldenkærne S, Hermansen C, Levin G, Wu S, Stisen S (2023) Water-table-driven greenhouse gas emission estimates guide peatland restoration at national scale. Biogeosciences 20(12):2387–2403. https://doi.org/10.5194/bg-20-2387-2023

Koolstofmarkt (2020) Method for determining co2 equivalent emission reductions. Co2-emission reduction through incease in groundwater levels in peatland areas (paying for peat). In: Green Deal National Carbon Market Consultation Group. https://nationaleco2markt.nl/wp-content/uploads/2020/06/AAA_GDNK-Groen-Veenweide-002-1-english_def_def.pdf. Accessed 5 Dec 2023

Leifeld J (2023) Carbon farming: Climate change mitigation via non-permanent carbon sinks. J Environ Manage 339:117893. https://doi.org/10.1016/j.jenvman.2023.117893

Leifeld J, Keel SG (2022) Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks. Geoderma 423:115971. https://doi.org/10.1016/j.geoderma.2022.115971

Leifeld J, Menichetti L (2018) The underappreciated potential of peatlands in global climate change mitigation strategies. Nat Commun 9(1):1071. https://doi.org/10.1038/s41467-018-03406-6

Leifeld J, Lupascu M (2023) Climate impact of peatland agriculture. In: Peatlands and climate change. Scientific facts and figures for decision-makers., Strack M (ed). International Peatland Society, Jyväskylä, Finland, pp 151–191

Lin F, Zuo H, Ma X, Ma L (2022) Comprehensive assessment of nitrous oxide emissions and mitigation potentials across european peatlands. Environ Pollut 301:119041. https://doi.org/10.1016/j.envpol.2022.119041

Lohila A, Minkkinen K, Laine J, Savolainen I, Tuovinen J-P, Korhonen L, Laurila T, Tietäväinen H, Laaksonen A (2010) Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. J Geophys Res: Biogeosciences 115(G4). https://doi.org/10.1029/2010JG001327

Mander Ü, Espenberg M, Melling L, Kull A (2023) Peatland restoration pathways to mitigate greenhouse gas emissions and retain peat carbon. Biogeochemistry. https://doi.org/10.1007/s10533-023-01103-1

Marshall L, Kelly A (2010) The time value of carbon and carbon storage: Claryfing the terms and the policy implications of the debate. WRI Working Paper, Washington, DC.: 23 pp. www.wri.org/publications. Available from www.wri.org/publications.. Accessed 5 Dec 2023

Millar RJ, Nicholls ZR, Friedlingstein P, Allen MR (2017) A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. Atmos Chem Phys 17(11):7213–7228. https://doi.org/10.5194/acp-17-7213-2017

Moura Costa P, Wilson C (2000) An equivalence factor between co2 avoidedemissions and sequestration – description andapplications in forestry. Mitig Adapt Strat Glob Change 5(1):51–60. https://doi.org/10.1023/A:1009697625521

Murray BC, Sohngen B, Ross MT (2007) Economic consequences of consideration of permanence, leakage and additionality for soil carbon sequestration projects. Clim Change 80(1):127–143. https://doi.org/10.1007/s10584-006-9169-4

Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H (2013) Anthropogenic and natural radiative forcing. In: Climate Change 2013: The physical science basis. Working Group I contribution to the IPCC fifth assessment report, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 659–740

Neubauer SC, Megonigal JP (2015) Moving beyond global warming potentials to quantify the climatic role of ecosystems. Ecosystems 18(6):1000–1013. https://doi.org/10.1007/s10021-015-9879-4

Novita N, Asyhari A, Ritonga RP, Gangga A, Anshari GZ, Jupesta J, Bowen JC, Lestari NS, Kauffman JB, Hoyt AM, Perryman CR, Albar I, Putra CAS, Adinugroho WC, Winarno B, Castro M, Yeo S, Budiarna T, Yuono E, Sianipar VC (2024) Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands. Sci Total Environ 952:175829. https://doi.org/10.1016/j.scitotenv.2024.175829

Nugent KA, Strachan IB, Roulet NT, Strack M, Frolking S, Helbig M (2019) Prompt active restoration of peatlands substantially reduces climate impact. Environ Res Lett 14(12):124030. https://doi.org/10.1088/1748-9326/ab56e6

Ojanen P, Minkkinen K (2020) Rewetting offers rapid climate benefits for tropical and agricultural peatlands but not for forestry-drained peatlands. Global Biogeochem Cycles 34(7):e2019GB006503. https://doi.org/10.1029/2019GB006503

Oldfield EE, Eagle AJ, Rubin RL, Rudek J, Sanderman J, Gordon DR (2022) Crediting agricultural soil carbon sequestration. Science 375(6586):1222–1225

Perryman CR, Bowen JC, Shahan J, Silviani PABD, Dayanti E, Andriyani Y, Asyhari A, Gangga A, Novita N, Anshari GZ, Hoyt AM (2024) Fate of methane in canals draining tropical peatlands. Nature Comm 15(1):9766. https://doi.org/10.1038/s41467-024-54063-x

Popkin R (2023) Shaky ground. Science 381:369–373. https://doi.org/10.1126/science.adj9318

Portmann R, Beyerle U, Davin E, Fischer EM, De Hertog S, Schemm S (2022) Global forestation and deforestation affect remote climate via adjusted atmosphere and ocean circulation. Nat Commun 13(1):5569. https://doi.org/10.1038/s41467-022-33279-9

Schlesinger WH (2022) Biogeochemical constraints on climate change mitigation through regenerative farming. Biogeochemistry 161(1):9–17. https://doi.org/10.1007/s10533-022-00942-8

Sierra CA, Crow SE, Heimann M, Metzler H, Schulze ED (2021) The climate benefit of carbon sequestration. Biogeosciences 18(3):1029–1048. https://doi.org/10.5194/bg-18-1029-2021

Tanneberger F, Appulo L, Ewert S, Lakner S, Brolcháin NÓ, Peters J, Wichtmann W (2021) The power of nature-based solutions: How peatlands can help us to achieve key eu sustainability objectives. Adv Sustain Syst 5(1):2000146. https://doi.org/10.1002/adsu.202000146

Tiemeyer B, Albiac Borraz E, Augustin J, Bechtold M, Beetz S, Beyer C, Drösler M, Ebli M, Eickenscheidt T, Fiedler S, Förster C, Freibauer A, Giebels M, Glatzel S, Heinichen J, Hoffmann M, Höper H, Jurasinski G, Leiber-Sauheitl K, Peichl-Brak M, Roßkopf N, Sommer M, Zeitz J (2016) High emissions of greenhouse gases from grasslands on peat and other organic soils. Glob Change Biol 22(12):4134–4149. https://doi.org/10.1111/gcb.13303

Tiemeyer B, Freibauer A, Borraz EA, Augustin J, Bechtold M, Beetz S, Beyer C, Ebli M, Eickenscheidt T, Fiedler S, Förster C, Gensior A, Giebels M, Glatzel S, Heinichen J, Hoffmann M, Höper H, Jurasinski G, Laggner A, Leiber-Sauheitl K, Peichl-Brak M, Drösler M (2020) A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. Ecol Ind 109:105838. https://doi.org/10.1016/j.ecolind.2019.105838

UNEP (2022) Global peatlands assessment – the state of the world's peatlands: evidence for action toward the conservation, restoration, and sustainable management of peatlands. Global Peatland

Initiative. United Nations Environment Programme, Nairobi, p 418. Available at https://www.unep.org/resources/global-peatlands-assessment-2022

VCS (2017) Vm0036. Methodology for rewetting drained temperate peatlands. https://verra.org/wp-content/uploads/imported/methodologies/vm0036-rewetting-drained-temperate-peatlands-v1.0.Pdf. Voluntary Carbon Standard. Accessed 5 Dec 2023

Wang Y, Calanca P, Leifeld J (2024) Sources of nitrous oxide emissions from agriculturally managed peatlands. Glob Change Biol 30(1):e17144. https://doi.org/10.1111/gcb.17144

Ward C, Stringer LC, Warren-Thomas E, Agus F, Crowson M, Hamer K, Hariyadi B, Kartika WD, Lucey J, McClean C, Nurida NL, Petorelli N, Pratiwi E, Saad A, Andriyani R, Ariani T, Sriwahyuni H, Hill JK (2020) Smallholder perceptions of land restoration activities: rewetting tropical peatland oil palm areas in sumatra, indonesia. Reg Environ Change 21(1):1. https://doi.org/10.1007/s10113-020-01737-z

West TAP, Börner J, Sills EO, Kontoleon A (2020) Overstated carbon emission reductions from voluntary redd+ projects in the brazilian amazon. Proceed National Acad Sci 117:24188–24194. https://doi.org/10.1073/pnas.2004334117

Wilson D, Blain D, Couwenberg J, Evans CD, Murdiyarso D, Page S, Renou-Wilson F, Rieley J, Sirin A, Strack M, Tuittila ES (2016) Greenhouse gas emission factors associated with rewetting of organic soils. Mires and Peat 17:04

Yu ZC, Loisel J, Brosseau DP, Beilman DW, Hunt SJ (2010) Global peatland dynamics since the last glacial maximum. Geophys Res Lett 37:L13402. https://doi.org/10.1029/2010gl043584