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Ideas and perspectives: Rethinking climate mitigation of afforestation and rewetting of temperate and boreal degraded organic soils

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Abstract. Degraded peatlands are among the largest land-based sources of greenhouse gas emissions in the European Union (EU). In response, the EU's climate change mitigation targets are driving efforts to reduce emissions and enhance carbon sequestration within the land-use sector. A significant challenge is the high emissions from organic soils, particularly those degraded by peat extraction and agriculture. This has sparked discussions on appropriate mitigation strategies. Rewetting is gaining attention, and concerns persist that afforestation may hinder rewetting efforts, thereby reducing climate change mitigation potential. However, such concerns often oversimplify both measures. Though many perceive afforestation and rewetting as competing strategies, these measures should ideally and alternately be implemented based on distinct local conditions and goals in different regions. This perspective evaluates their advantages and limitations using evidence from boreal and temperate peatlands. The paper highlights underappreciated, evidence-based arguments to support more nuanced stakeholder discussions and promote complementary, context-appropriate implementation of the measures.

1 Introduction

The climate policy goals of the European Union (EU) stipulate that, starting from 2030, the land use, land-use change, and forestry (LULUCF) sector must be climate neutral. To achieve EU-scale climate neutrality, by 2050, it is increasingly expected that LULUCF CO_2 sequestration and other Carbon Dioxide Removal (CDR) strategies should effectively compensate greenhouse gas (GHG) emissions in other sectors (UNFCCC, 2018; EC, 2023). This leads to discussions among EU member states, the European Commission, and other stakeholders, including researchers, about the most appropriate *climate change mitigation measures* (CCMMs).

Organic soils (Hiraishi et al., 2014) represent a major source of GHG emissions at the EU scale and are therefore a priority for nature-based climate change mitigation measures. In particular, peat extraction fields and agricultural lands with drained

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organic soils are typically characterized by significantly higher GHG emissions compared to other organic soil land-uses (Leskinen et al., 2018). Therefore, targeted CCMMs are necessary for these areas. Both rewetting and afforestation are frequently referred to as the most effective land-use-based CCMMs in such degraded peatland areas (Leifeld and Menichetti, 2018; Chiti et al., 2024).

Rewetting has been recognized as an appropriate strategy for the sustainable management of areas with drained organic soils (Eggleston et al., 2006). Frequently, drained organic soils are historical peatlands where the water table has been lowered to promote specific economic activities – peat extraction, agriculture, or forestry. Rewetting targets the restoration of soils to a wet state to reduce the rate of organic matter decomposition (Hiraishi et al., 2014). This reduces oxidation and the release of stored carbon into the atmosphere from soil carbon stocks (Darusman et al., 2023). When rewetting aims at ecological restoration, inundating or saturating the soil with water for all or a part of the year, biota adapted to these partly anoxic conditions, such as peat mosses, are expected to reinitiate the accumulation of soil carbon as peat (Bianchi et al., 2021).

Afforestation is commonly recognized as a CCMM, primarily due to its widely acknowledged capacity for high and rapid carbon sequestration in living biomass compared to other land uses. Afforestation primarily (but not exclusively) involves maintaining the drained state of organic soils to ensure forest stand productivity. Accordingly, in this paper, we consider afforestation on already drained organic soils only. Drainage ensures that there is sufficient oxygen availability in the rooting zone, which is necessary for enhanced tree growth. Afforestation is often considered controversial due to concerns about soil carbon stock loss and the potential ineffectiveness of harvested wood products (HWP) in storing carbon over the long term.

Challenges associated with both measures in the context of climate change mitigation lie in managing the expected soil carbon sequestration and the reduction of GHG emissions. Both are influenced not only by current and historical land use and management—reflected in hydrology, vegetation, and soil properties—but also by meteorological conditions and topography (Wilson et al., 2016a). Such variation in potential outcomes makes the quantification of spatially and temporally variable soil GHG emissions particularly challenging. Assessing changes in soil carbon stocks is further complicated by relatively small annual variations, as the yearly soil carbon balance fluctuates around an equilibrium between carbon losses from organic matter decomposition and leaching, and carbon inputs from plant litter (Straková et al., 2011). In addition, the role of carbon stored in living biomass, HWPs and associated substitution effects must also be considered for both rewetting and afforestation areas. Altogether, these factors determine the overall impact of rewetting and afforestation on land-use-related GHG emissions and the net carbon balance.

Increased gross CO_2 emissions from drained soils are commonly assumed to lead to a persistent net loss of soil carbon, while rewetting is often assumed to promote peat accumulation. Consequently, there is noticeable concern that the afforestation on drained organic soils could result in continued high emissions (Jurasinski et al., 2024). Neither of these assumptions and concerns, however, are fully supported by the available scientific evidence. Differences of opinion and disagreements among stakeholders are primarily driven by misunderstandings about the respective impacts of afforestation and rewetting on land use-related GHG emissions. Discussions are often based on common misconceptions which oversimplify crucial aspects of rewetting and afforestation.

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In our view, current discussions on afforestation and rewetting often place strong emphasis on the anticipated climate benefits of rewetting while giving comparatively less attention to its associated risks. The potential contribution of afforestation tends to be underrepresented. Typically, analysis focuses on afforestation or rewetting separately, and there is a lack of a comparative and critical examination of both measures from a climate perspective. The novelty of our perspective lies in the comparative evaluation of afforestation and rewetting within a common framework, focusing on aspects that are often overlooked in current stakeholder discussions and synthesizing underrepresented perspectives.

Our deliberate emphasis on underrepresented aspects aims to stimulate critical thinking, counterbalance what we perceive as an imbalance in current discussions that often place greater emphasis on the climate benefits of rewetting despite substantial uncertainties in its greenhouse gas emissions, and encourage a more balanced and evidence-based consideration of both mitigation approaches by acknowledging the often downplayed strengths, limitations or uncertainties associated with each. The assessment we undertook is based on the results of recent synthesis studies (e.g. Jauhiainen et al., 2023; Bianchi et al., 2021; Myllyviita et al., 2021; Darusman et al., 2023). Further, we draw on observations from relevant international research on boreal and temperate peatlands. Instead of focusing solely on the impacts of afforestation and rewetting on soil greenhouse gas emissions, we provide a broader perspective that also considers the role of harvested wood products, which we argue is essential for an objective comparison of afforestation and rewetting as CCMs. Although the policy discussion which prompted this perspective is focused on the EU, the arguments presented may also be applicable to boreal and temperate peatlands in other parts of the world.

The **Aim** of this contribution is therefore: i) to inform scientific discourse and stakeholder engagement by providing a structured comparison of the climate roles of rewetting and afforestation of agricultural organic soils and peat extraction sites within a common analytical framework involving land areas of interest, soil carbon stock changes, soil GHG emissions, and carbon sinks in living biomass and HWP; and ii) to promote a more nuanced discussion that seeks a responsible and balanced implementation of both rewetting and afforestation to achieve climate goals based on evidence-based decision-making.

2 Relevant land areas for afforestation and rewetting

There are no "*superior*" solutions for ecosystem carbon sequestration (Baldocchi and Penuelas, 2019) or single best interventions (Worrall et al., 2009). Outcomes of CCMMs are subject to and determined by specific local conditions (Wilson et al. 2016b). Planning of CCMs is further complicated by policy requirements to deliver ecological co-benefits. However, measures that maximize climate mitigation outcomes often involve ecological trade-offs; therefore, careful assessment of target areas is essential. (Palmer and Filoso, 2009). Nevertheless, afforestation and rewetting should not be considered competing measures, as each requires areas with distinct site characteristics for effective implementation. Under the right conditions, both measures can effectively complement each other at the regional scale, allowing strategies to be balanced to maximize the cumulative impacts across different areas (Worrall et al., 2009). It is therefore crucial to carefully assess the specific local conditions of degraded organic soils (historical or current peatland), to decide whether it is more beneficial to

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afforest an area for enhanced climate and economic gain, or to ecologically restore a peatland ecosystem for balanced climate and ecological benefits. Accordingly, peatland degradation indicators such as soil bulk density, organic matter quality, organic carbon stocks, C:N ratio, pH, and macronutrient levels are essential for informed decision-making.

Agricultural lands with organic soils are associated with high climate risks (Erkens et al., 2016; Liang et al., 2024). Though historically these were peatlands, long-term cultivation has led to significant decomposition of organic substrates and degradation. The soil conditions in such areas have frequently been irreversibly altered, greatly reducing the potential for successful rewetting (Holden et al., 2004; Richert et al., 2000; Kreyling et al., 2021) and effectively disqualifying this measure as an option (Vanselow-Algan et al., 2015). Due to historical soil fertilization and altered pH, where water resources are insufficient, rewetting can result in unexpected GHG emissions and nutrient leaching (Basiliko et al., 2007; Ardón et al., 2010; Harpenslager et al., 2015).

Forests can sequester significantly more CO_2, and forested soils emit fewer GHGs than agricultural lands (Minkkinen et al., 2018; European Environment Agency, 2023). Afforestation thus frequently represents an optimal CCMM for such areas (Chiti et al., 2024). This approach provides ecological co-benefits, especially where afforestation is in fact reforestation, as many organic soils occur in agricultural areas that were previously naturally developed into wetland forest before being cleared. Therefore, afforestation in such areas can be treated as restoration. In these lands and in peat extraction fields, afforestation can also be combined with rewetting to restore wetland forests (Hoffmann et al., 2017; Priedītis, 2014; Jurasinski et al., 2020), thereby contributing to the conservation of natural wetland habitats, such as alluvial forests, Fennoscandian deciduous swamp woods, and bog woodlands (European Commission, 1992). In this way, afforestation and reforestation can be considered measures that support the objectives of ecological policies and goals, such as the Nature Restoration Law, which requires habitat re-establishment as a key component of achieving forest habitat connectivity.

The general preconditions for the successful implementation of rewetting are achieving wet soil and the introduction of typical wetland biota (Hiraishi et al., 2014). This can be challenging due to the difficulty in restoring degraded peat (Beyer et al., 2021), water table fluctuations, uneven terrain (Tuittila et al., 2003), and climate change (Beyer et al., 2021). Successful rewetting requires specific conditions such as suitable soil conditions (Kitson and Bell, 2020) and the ability to maintain a stable, elevated water table (Zhong et al., 2020). Soil quality preconditions for considering an area suitable for rewetting include high organic carbon stocks, a low degree of peat degradation, and low pH and nutrient levels. Merely raising the water table is not enough and additional measures such as topography adjustment and fertile topsoil removal may be required (Huth et al., 2020; Weil et al., 2020) to ensure conditions necessary for the introduction and maintenance of wetland-specific biota (Wilson et al. 2007; Wilson et al. 2016b). Prioritizing areas adjacent to pristine wetlands (with no direct management impact) or those with nonfunctional drainage systems, therefore, increases the likelihood of rewetting success, as these areas are more likely to ensure the necessary conditions (Kitson and Bell, 2020). Moreover, they pose fewer legal, ecological and economic risks for adjacent areas (Grygoruk et al., 2015; Breznikar et al., 2024; Pönisch et al., 2023; Mackin et al., 2017).

Even the rewetting of former peat extraction fields requires careful planning. Typically, it is assumed that all peat extraction sites are suitable for rewetting due to their large soil carbon stocks, associated soil carbon stock preservation potential and

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assumed nutrient-poor conditions. However, large organic soil carbon stocks alone do not provide adequate justification for the spatial and temporal effectiveness of rewetting. The removal of the peat layer exposes deeper, more nutrient-rich soil horizons and, where surface elevation is sufficiently reduced, facilitates groundwater influence on surface layers. This can alter nutrient conditions, particularly in cases of nutrient-rich water inflow. This can lead to increased GHG emissions (Huth et al., 2020), ultimately undermining rewetting-related climate change mitigation goals if achieved soil carbon sequestration cannot offset increased CH_4 and N_2O emissions. Another aspect related to altered nutrient conditions limiting the suitability of rewetting is the promotion of natural forest succession, which makes the restoration of mires difficult or impossible (Figure 1). For these reasons, former peat extraction sites with nutrient-poor soil make more suitable targets for rewetting - if the raised water table can be maintained. This approach not only reduces or avoids the loss of soil carbon stocks, it also further facilitates peatland restoration.

Figure 1: Illustrative example of a rewetted former peat extraction site in Lille Vildmose, Denmark (56.910340, 10.184330). Several years after rewetting as part of mire restoration, the site continues to experience extensive natural tree regeneration despite management efforts to maintain open mire conditions. On one side of the rewetted area, repeated removal of tree seedlings is carried out to limit forest succession, whereas unmanaged areas have developed dense stands of young trees. This example illustrates the practical challenge that rewetting efforts alone do not necessarily guarantee successful mire restoration and that restoration outcomes may depend on site-specific hydrological and ecological conditions. The persistent natural forest succession in this example, despite repeated management interventions, highlights that restoration objectives may conflict with natural ecosystem development and may require long-term, active management to maintain the desired habitat. This raises the question of whether, under some site conditions, allowing natural succession towards forest could provide a more sustainable and effective long-term management strategy than continued efforts to maintain open mire conditions.

In cases of irreversibly altered peat conditions where rewetting of peat extraction sites is not a viable option from either a climate or an ecological perspective, afforestation with maintained drainage can provide a meaningful alternative (Figure 2) and can represent a more effective CCMM, as nutrient uptake by trees promotes biomass growth and may reduce the risk of unexpected soil GHG emissions. Alternatively, such sites may also be repurposed for paludiculture (Aleksāns et al., 2019), including the cultivation of wet soil adapted woody species (e.g., black alder, birch) and herbaceous crops such as reeds or sphagnum moss (EU, 2024).

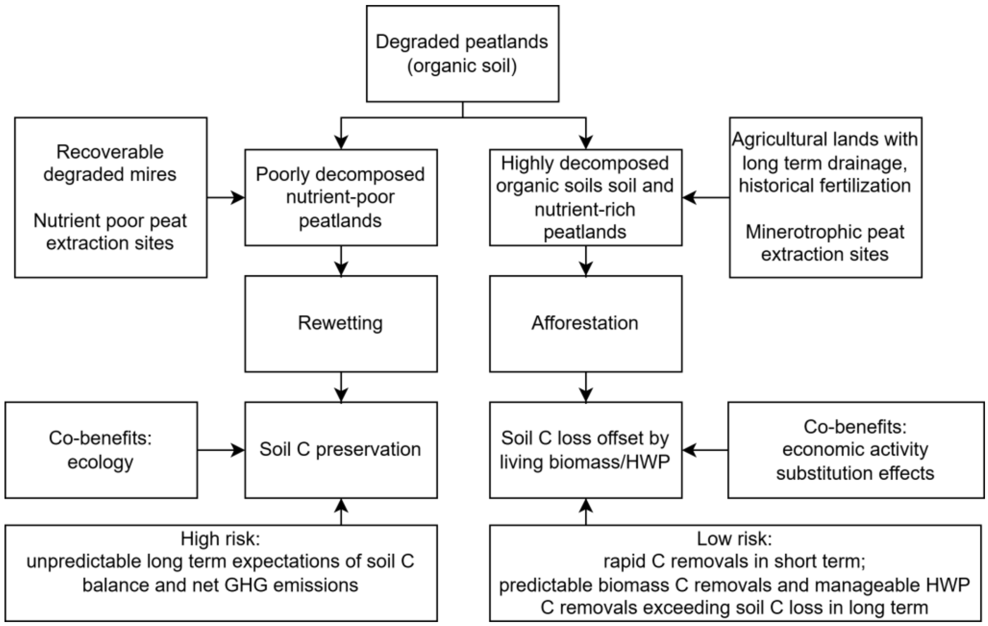

Figure 2: Areas suitable for rewetting and afforestation, and benefits of the measures. Afforestation and rewetting do not compete for land, as each requires distinct conditions for effective implementation: recoverable, nutrient-poor peatlands with high carbon stocks are suitable for rewetting, whereas irreversibly degraded, highly decomposed organic soils and peatlands with altered (nutrient-rich) conditions are more suitable for afforestation.

3 Soil carbon stock changes

Soil carbon stocks are the central element in assessing the appropriateness of rewetting as a CCMM, as its primary objective is to preserve existing soil carbon; therefore, its effectiveness depends on the presence of substantial soil carbon pools. Where such stocks are limited, the mitigation potential of rewetting is correspondingly reduced. The same reasoning applies to restoration, as its success generally declines with increasing soil degradation, indicated by organic matter loss. Conversely, afforestation is often considered to negatively affect soil carbon stocks and is therefore criticized as an unsuitable measure, despite biomass accumulation and HWP substitution effects can offset these losses. Concerns about afforestation-related drainage compromising organic soil carbon stocks (Jurasinski et al., 2024) originate from the higher mineralization rates observed in drained soils (Beaulne et al., 2021).

Historical drainage, however, does not necessarily mean that carbon stocks are currently at risk. In ecosystems, especially in cool, wet climates like the Nordic regions (boreal and hemiboreal zones) with extensive peatland areas, the balance between drained organic soil carbon loss and input (Bārdule et al., 2021) can be sustained, allowing carbon stocks to stay stable or even increase (Jauhiainen et al., 2023; Butlers et al., 2026, 2025). Factors like time since drainage or rewetting, soil nutrient status, climate, and vegetation play a key role in determining the variation of soil carbon stock change.

Afforestation is typically implemented on previously drained and degraded soils, ***not*** in pristine areas. Thus, at the EU scale, afforestation does not promote drainage and soil degradation. On the contrary, the more degraded the soil (including lower

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carbon stocks) at the time of afforestation, the greater the potential for positive impacts on soil carbon. Afforestation is recognized as a practice that efficiently sequesters carbon in living biomass (Hommeltenberg et al., 2014; Meyer et al., 2013; Hargreaves et al., 2003), thereby providing the best potential for converting highly degraded lands (ecosystems) into carbon sinks (Sanz et al., 2017; Vesterdal and Leifeld, 2010; Liu et al., 2024). Afforesting agricultural soils that have long been drained and are highly decomposed reduces mineralization promoted by cultivation (intensive and regular soil management) and increases soil carbon inputs (Hu et al., 2016; Lal, 2005; Feng et al., 2022). Increased soil carbon input results from the increase in biomass litter, including natural mortality and harvesting residues (Minkkinen et al., 2018). These additional carbon inputs can offset soil carbon losses from CO_2 emissions. This helps to prevent further soil carbon loss through mineralization and erosion and can transform the soil into a carbon sink (Liu et al., 2024). Since previously drained and recently afforested peatland soils with high carbon content can act as carbon sinks (Hermans et al., 2022), soil carbon removals can also be expected when afforesting peat extraction fields (Jauhiainen et al., 2023).

Quantifying soil carbon stock changes is challenging, especially when assessing the impacts of management interventions, including afforestation and rewetting. Typically, cumulative measured soil carbon losses and inputs (i.e., net soil carbon stock changes) fluctuate around equilibrium with high uncertainty. In addition, spatial and temporal variability further increase uncertainty, as carbon stock changes vary both intra- and interannually. However, while the soil carbon balance fluctuates with changing meteorological conditions, forest growth stages (Butlers et al., 2025) and management (Samariks et al., 2026), there are indications that in cooler climates, afforested, drained, and particularly nutrient-poor organic soils can maintain or increase their carbon stocks (Jauhiainen et al., 2023; Butlers et al., 2026, 2025).

Notably, nutrient-rich organic soils may exhibit a higher risk of carbon loss (Lazdiņš et al., 2024). However, in boreal forests, which are predominantly coniferous, soils are generally nutrient-poor. Therefore, in specific drained areas, organic soil carbon stocks have been preserved or have even increased (Minkkinen et al., 2018; Butlers et al., 2022, 2025). To the best of our knowledge, this is because the principal impacts from drainage have occurred historically (Zhang et al., 2020), for the most part, within the first few decades after the land was initially drained (Jauhiainen et al., 2023; Hargreaves et al., 2003; Ghezelayagh et al., 2024). The rate of peat carbon loss after drainage consistently decreases over time since drainage (Nguyen et al., 2025; Qiu et al., 2021), therefore, lands drained around the middle of the previous century (Zālītis, 2012) have had time to stabilize and frequently exhibit sustainable carbon stocks (Liu et al., 2024; Rodrigues et al., 2003).

Nevertheless, the main uncertainty of afforestation with maintained drainage remains the probability that soil carbon stocks continue to diminish. The CCM potential of afforestation land thus largely depends on whether, and to what extent, soil carbon is lost before reaching stability. Soil organic matter mineralization rates increase in warmer climates (Jauhiainen et al., 2023); therefore, the risk of prolonged soil carbon stock loss is higher in temperate zone. Thus, in this region, aiming for increased soil carbon removals through afforestation can be meaningfully combined with rewetting (Trettin and Jurgensen, 2002).

Rewetted soils are expected to become carbon sinks over time. However, the long-term effects are uncertain (Hambley et al., 2018) due to the limited number of studies (Nugent et al., 2018), rewetting dependence on unpredictable variability in the water table (Bacon et al., 2017), and vegetation development (Beyer et al., 2021; Koch et al., 2017; Richert et al., 2000;

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Kreyling et al., 2021). Previous rewetting attempts incorporating scientific carbon balance monitoring in different climatic regions have returned varying results. Even with restoration efforts in place, rewetting does not always lead to the successful replication of previous positive rewetting experiences. Thus, the results of specific positive studies cannot be generalized to all rewetting cases.

A meta-analysis of 28 scientific articles comparing degraded and rewetted peatlands showed that, in most cases, rewetting has not resulted in significant impact on CO_2 emissions. When further stratified by climatic regions, the results showed that while rewetting had a significant impact on CO_2 emissions in temperate peatlands, its effect in boreal peatlands has been small and insignificant (Darusman et al., 2023; Nakagawa et al., 2017). Such results raise serious concerns as to whether expectations that rewetting will unambiguously create soil carbon sinks have been overly optimistic.

Soil carbon sink expectations typically have been based on using pristine peatlands as a benchmark for rewetting. This, however, introduces important estimation errors, since conditions differ between pristine and rewetted sites (Koch et al., 2017; Jurasinski et al., 2020). Further, while peatlands have historically acted as carbon sinks, today's changing climate conditions limit the potential for rewetting to increase soil carbon stocks (Beyer et al., 2021; Updegraff et al., 2001; Silvius, 2007; Holden et al., 2004). Nowadays, even pristine peatlands do not always function as carbon sinks and are increasingly challenged by climate change impacts (Wilson et al., 2016a). This is illustrated in projections suggesting that bogs will continuously sequester less carbon, and fens characterized with higher nutrient availability may become carbon sources (Wu and Roulet 2014; Zhong et al. 2020). Rewetting sites are even more susceptible to becoming a carbon source due to fluctuations in the water table (Wilson et al. 2016b). Consequently, rewetted soils can have a stronger warming effect than pristine wetlands (Wilson et al., 2016a). Under conditions of increasing drought frequency (Rahmstorf and Coumou, 2011; Stott, 2016), rising evapotranspiration trends and a declining water table (Zhong et al., 2020), the emission response of rewetting is unpredictable (Chu et al., 2015; Kozub et al., 2024; Brangarí et al., 2021). This raises concerns about rewetting's long-term efficiency.

Peatlands can, in fact, remain CO_2 sources for decades after rewetting (Vanselow-Algan et al., 2015; Samaritani et al., 2011), and when specific rewetted sites, if ever, will turn into carbon sinks remains unknown. In areas facing water scarcity and declining hydrological function, even restored peatlands can continue to lose carbon due to challenges in maintaining a high water table, caused by irregular rainfall and increased evapotranspiration (Ghezelayagh et al., 2024). Reducing soil carbon loss from rewetting typically requires the minimization of mineralization processes. This can be achieved if consistent water saturation is maintained. If the water level drops, especially during warmer months, relatively low litter carbon input from open wetland vegetation may be insufficient to compensate for a rapid increase in labile organic matter decomposition (Barnard et al., 2020), leading to soil carbon losses of up to 1.71 t CO_2-C ha^{-1} $year^{-1}$ (Hiraishi et al., 2014). The success of rewetting also relies on the development of wetland-specific vegetation, which is not assured (Wilson et al., 2016a).

Fluctuations in the water table are associated with reduced biomass growth (Kozub et al., 2024), limited soil carbon inputs, and significantly increased emissions from the soil (Van De Riet et al., 2013; Vanselow-Algan et al., 2015). Labile organic matter stored during the wet season quickly decomposes in dry and warm seasons when the water table is lowered (Richert et al., 2000; Zhong et al., 2020). Even under the conditions of an elevated water table, both on-site and off-site CO_2 emissions

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can be expected (Van De Riet et al., 2013; Franz et al., 2016; Hambley et al., 2018), thereby deviating from the expected net carbon balance (Hambley et al., 2018). Soil carbon is lost through runoff and leaching can lead to carbon losses of up to 0.51 t CO_2-C ha^{-1} year^{-1} (Hiraishi et al., 2014). Rewetting outcomes are thus unpredictable and vary with site conditions (Wilson et al. 2016b; Hambley et al. 2018). Therefore, rewetting cannot guarantee carbon preservation (Franz et al., 2016; Bacon et al., 2017). Consequently, it is more appropriate to approach rewetting as a strategy for reducing soil carbon losses, as opposed to a reliable strategy for increasing carbon stocks (Wilson et al., 2022).

4 Soil GHG emissions

When evaluating afforestation and rewetting, the analysis typically focuses on soil carbon stock changes, while overlooking non-CO_2 GHG emissions such as nitrous oxide (N_2O) and methane (CH_4). This leads to biased CCMM expectations. Non-CO_2 emissions are particularly relevant, as they are characterized by high variability, poorly understood emission drivers, and difficulties in quantification and prediction, as well as higher global warming impacts.

The efficiency of afforestation has been demonstrated by reduced soil GHG emissions when compared to agricultural or peatland extraction sites (Hiraishi et al., 2014; Jauhiainen et al., 2023). In addition, temperate and boreal drained forest ecosystems function not only as a carbon sink (Minkkinen et al., 2018; Ojanen et al., 2013; Meyer et al., 2013; Hommeltenberg et al., 2014), but also ensure net GHG removals (Minkkinen et al., 2002; Ojanen et al., 2013; Lohila et al., 2011). Therefore, the afforestation of degraded organic soils is expected not only to reduce GHG emissions, but also to transform these areas from net GHG emission sources to sinks (Hommeltenberg et al., 2014; Hargreaves et al., 2003; Meyer et al., 2013). However, afforestation also carries inherent uncertainty regarding the expected net GHG impacts. It is commonly assumed that forest operations increase soil GHG emissions; however, this remains uncertain and the net effect is not well known. While soil disturbance from harvesting or site preparation may increase emissions, associated changes such as rising groundwater levels, moisture accumulation, soil compaction or soil drying can act as emission inhibitors, making the overall impact unclear. Although elevated emissions are often observed after harvesting, there is limited evidence that they originate from the decomposition of existing soil organic matter. Instead, a substantial share likely derives from the decomposition of fresh litter inputs, including harvesting residues, hence not contributing to a net GHG emissions. Despite management impacts, GHG emissions in afforested lands with sustained drainage are expected to remain relatively stable; nevertheless, this is an area that requires further investigation.

Inundated soils can release higher amounts of unpredictable non-CO_2 emissions (Wilson et al., 2009, 2007; Vanselow-Algan et al., 2015). Thus, the underestimation of non-CO_2 emissions is particularly relevant in the case of rewetting, as it is often incorrectly assumed that N_2O emissions from wet soils are negligible (Hiraishi et al., 2014). Likewise, the impact of uncertainty is not sufficiently discussed with respect to CH_4. Recent studies illustrate that N_2O emissions from wet soils can be comparable to those from drained forest soils within the margin of error due to flux variability in local conditions (Lin et al., 2022; Gios et al., 2024). While the N_2O emissions are low in absolute value, their role in the GHG balance should not be overlooked, given

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that their 100-year global warming potential (GWP) is 265 times greater than CO_2 (Huang et al., 2013). This is particularly relevant for agricultural lands, where nitrogen from past farming practices still resides in the soils, or when rewetting peatlands for paludiculture, which requires nitrogen fertilization, leads to substantial GHG emissions (Gios et al., 2024; Bodelier and Laanbroek, 2004).

CH_4, with a 100-year GWP 28 times that of CO_2 (Huang et al., 2013), presents an additional challenge. Especially in nutrient-rich soils, rewetting can trigger CH_4 hotspots (Hiraishi et al., 2014) that are difficult to predict and control (Cresto Aleina et al., 2016), potentially negating their climate benefits (Boucher et al., 2009). Though some argue that CH_4's comparatively short lifespan means its impact is marginal (Günther et al., 2020), this view oversimplifies the problem by assuming the predictability of highly uncertain emissions (Joabsson et al., 1999). Further, even though the radiative forcing of assumed CH_4 emissions plateaus due to their short lifespan (Günther et al., 2020), they still contribute to long-term climate warming (Neubauer and Megonigal, 2015). Such effects are determined by continuous CH_4 emissions and their relatively rapid oxidation into CO_2, enabling CH_4 to continue warming the atmosphere even after its initial effects subside.

Consequently, if wet soils do not ensure sufficient carbon removal, CH_4 contributes to net CO_2 emissions. Furthermore, the time required for CH_4 emissions to stabilize after rewetting remains unknown. Studies indicate that CH_4 emissions have shown an increasing trend over time during the first years after rewetting (Darusman et al., 2023). Thus, the assumption that CH_4 emissions remain constant (Günther et al., 2020) provides inaccurate predictions, especially since CH_4 emissions are highly sensitive to regional changes in temperature and precipitation (Aalto et al., 2024). These factors cause emissions to fluctuate, potentially varying by as much as 3 to 6 times around the average (Hiraishi et al., 2014).

When considering the occurrence of N_2O emissions and increased CH_4 emissions from rewetted agricultural soils, empirical evidence demonstrates that rewetting can result in global warming impacts comparable to those of drained, forested soils (Figure 3) even over a 500-year timeframe (Figure S1). For these reasons, the projected rewetting benefits of expected negative radiative forcing may only materialize after several centuries (Neubauer, 2014; Petrescu et al., 2015a), or even a millennium (Anderson et al., 2016). In the shorter term, increased CH_4 emission rates (Neubauer and Megonigal, 2015; Vanselow-Algan et al., 2015) can be expected to exceed the anticipated (but not guaranteed) CO_2 removal rates (Petrescu et al., 2015b; Whiting and Chanton, 2001).

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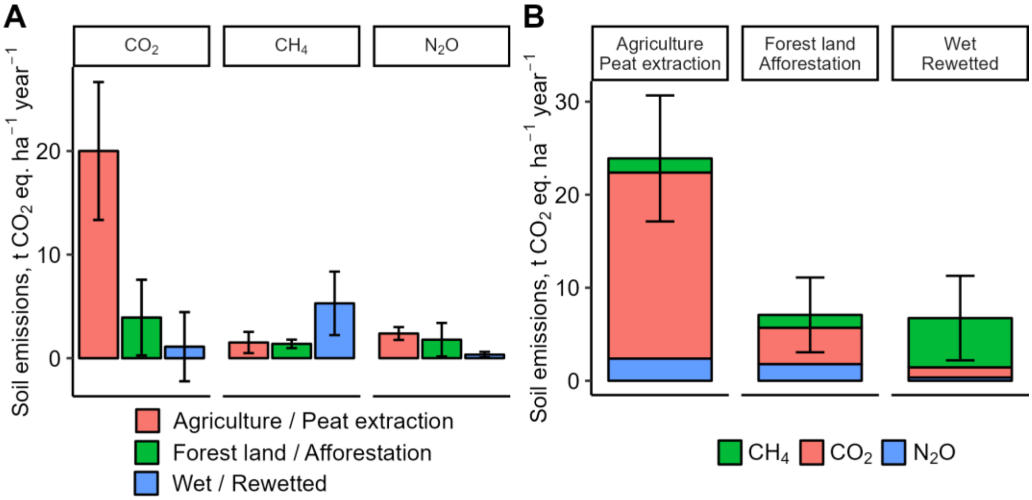

Figure 3: Greenhouse gas emissions from peatlands under agricultural use, peat extraction, afforestation, and wet or rewetted conditions. On average, soils under agricultural use and peat extraction are significant sources of emissions, releasing 20.0 ± 6.7 t CO_2 ha^{-1} year^{-1}. In comparison, afforested and forest lands emit between 0.3 and 7.6 t CO_2 ha^{-1} year^{-1} (mean: 3.9 ± 3.7), while wet and rewetted soils show a wider range—from carbon sinks to sources—with mean emissions of 1.1 ± 3.3 t CO_2 ha^{-1} year^{-1}. N_2O and CH_4 emissions are nearly equal across drained sites, whereas wet and rewetted soils exhibit increased CH_4 and reduced N_2O emissions (Panel a). Cumulative soil GHG emissions from afforested and forest lands (7.1±4.0 t CO_2 eq. ha^{-1} year^{-1}) are indifferent to those from wet and rewetted soils (6.7±4.5 t CO_2 eq. ha^{-1} year^{-1}), both in the 100-year perspective (panel b) and over 500 years (Figure A1). Averages in higher-disaggregation categories derived from the same data are presented in Figure A1. The emission-factor selection, harmonisation, averaging, uncertainty propagation, and calculation of CO_2 equivalents are described in Appendix B, and the underlying emission factors are reported in Table A1.

5 The Carbon sink of living biomass and harvested wood products

When evaluating afforestation and rewetting, it is crucial to consider the total amount of living biomass in forested lands and wetlands. The inefficiency of carbon sequestration under rewetting is indicated by comparably lower primary productivity, especially in northern peatlands (Baldocchi and Penuelas, 2019). Paludiculture can enhance biomass growth, which is often harvested to produce short life-cycle products. But it faces challenges such as low soil bearing capacity (Schröder et al., 2015), which limits the ability to harvest biomass without causing soil disturbances and related GHG emissions. This renders profitability and long-term feasibility uncertain (Wichmann and Köbbing, 2015; Becker et al., 2020; Wichmann et al., 2017, 2020; de Jong et al., 2021; Wichmann, 2017, 2021; Schröder et al., 2015), especially compared to afforestation, where forest management and wood production offer more predictable benefits. Carbon removals from biomass growth following afforestation may be affected by natural disturbances. The consequences of natural disturbances like forest fires, wind damage or pests, however, are easy to manage due to the possibility of rapidly restarting the forest management cycle through reforestation. Furthermore, natural disturbances typically do not result in the complete loss of living biomass carbon stocks, and biomass can be harvested, helping to mitigate their consequences.

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Temperate and boreal forests with drained organic soil provide a net carbon sink due to annual tree biomass growth (Minkkinen et al., 2018) achieving carbon sequestration rates between 2 and 35 t CO_2 ha^{-1} $year^{-1}$ (Chiti et al., 2024). These values considerably exceed the carbon removals expected from rewetting which ranges from annual removals of 1.70 t CO_2 ha^{-1} to emissions of 3.50 t CO_2 ha^{-1} (Bianchi et al., 2021). In addition, when trees are harvested, the cycle of carbon sequestration continues as the forest regenerates and harvested wood products (HWPs) extend the carbon sink beyond the forest. There are, however, limitations in quantifying and tracking the carbon sink associated with HWPs. International trade, as well as the often unknown use and reuse of wood products, in particular, complicate tracking their full life cycle and associated carbon stock changes, thereby limiting the ability to quantify the HWP carbon sink potential for offsetting soil carbon losses. These uncertainties are often used to downplay the potential climate benefits of HWPs. While tracking the complete life cycle of harvested wood products is indeed challenging, this does not imply that the carbon sink created by these products does not exist. Furthermore, soil carbon loss cannot continue indefinitely, and eventually it will reach an equilibrium under consistent land management practices (Liu et al., 2024; Rodrigues et al., 2003). Therefore, reliance on HWPs to compensate potential soil carbon losses is temporary and diminishes with lower initial soil carbon stocks at the moment of afforestation. The risk if further mitigated by the HWP carbon pool accumulating out-of-forest carbon with each subsequent forest management cycle (Trettin and Jurgensen, 2002). Further, depending on use, HWPs substitute non-renewable materials and the energy (Myllyviita et al., 2021; Sathre and O'Connor, 2008) required to produce more energy-intensive products (Bozzolan et al., 2024). Consequently, HWPs both extend the carbon sink and provide a substitution-related reduction of GHG emissions. The substitution effect is the most overlooked benefit of afforestation, despite contributing to climate change mitigation to a much greater extent than the HWP carbon sink. This is because, depending on the life cycle, HWP carbon stocks are ultimately returned to the atmosphere, and only a fraction accumulates in long-term sinks across multiple forest management cycles. Despite this eventual oxidation, the substitution effect of HWPs has a lasting impact through avoided emissions. Each kilogram of carbon in HWPs used as a substitute for non-wood products is estimated to avoid between -0.7 to 5.7 kg of carbon emissions (Leskinen et al., 2018). When substitution effects are accounted for, estimates show that intensive forest management provides greater carbon removals, including avoided emissions, compared to the alternative scenario of storing carbon in old-growth forests (Figure 4) (Jansons et al., 2025). In this manner, countries with developed forestry sectors can offset substantial GHG emissions (Johnston and Radeloff, 2019). At the end of the HWP life cycle, carbon returns to the atmosphere through combustion, offering an additional substitution effects by replacing fossil fuel sources.

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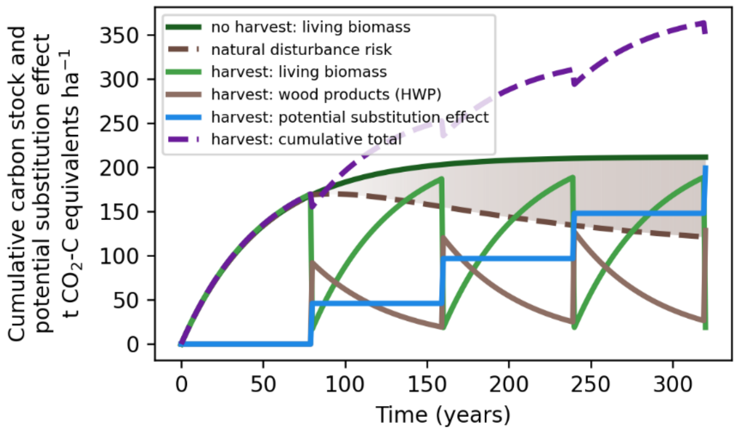

Figure 4: Conceptual illustration of the role of harvested wood products (HWP). While most carbon stored in HWP returns to the atmosphere according to commonly assumed product half-lives, a fraction accumulates across successive forest management cycles. Nevertheless, the climate mitigation effect of the HWP pool is considerably smaller than the impact of substitution. Even a modest substitution factor (e.g., 0.5) sustained over several cycles can lead to permanently avoided emissions comparable to the carbon stock of old-growth forests, where risks of carbon loss may increase over time.

Under a constant harvest rate and wood utilization practice, the HWP carbon stock tends to reach an equilibrium within a few decades (Bozzolan et al., 2024). Forestry and wood processing practices are not static, however, and develop continuously. Related afforestation risks overestimating HWP role can thus be mitigated by the market economy and policies tied to the production and consumption traditions of wood products. Improving forest management, and adjusting timber supply (Ménard et al., 2023) and demand can increase the HWP carbon sink over time (Joabsson et al., 1999), promoting afforestation's continued contribution to climate goals. Comprehensive accounting of both production and consumption of wood products already shows that the HWP carbon pool has been consistently increasing in individual countries and globally (Zhang et al., 2020). Strategic planning and continuous technological advancement in wood and its related industries can prolong the carbon cycle and sink potential (Bais-Moleman et al., 2018; Mair and Stern, 2017; Vis et al., 2016). This can be achieved by promoting processing efficiency to accelerate the inflow rate to the HWP carbon pool and by developing innovative wood products with longer service lives to reduce the outflow rate (Zhao et al., 2022). Reducing the use of wood as biofuel and increasing the production of durable wood products can increase both the HWP carbon sink and its substitution potential multiple times (Bozzolan et al., 2024). The reuse and recycling of wood products also adds to this potential, especially as countries shift focus away from wood biofuels (Bais-Moleman et al., 2018; Mair and Stern, 2017; Vis et al., 2016). Building long-lasting wooden structures can further multiply the global carbon stocks stored in HWPs (Churkina et al., 2020; Nabuurs et al., 2022). The HWP sink can be further promoted by implementing more accurate accounting methods in inventories of LULUCF GHG emissions (Trettin and Jurgensen, 2002).

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6 Future Directions and Research Needs

An important challenge of CCMMs is an accurate assessment of their impacts, which is necessary for informed decision-making, tracking progress toward climate targets, and their integration into carbon farming schemes. The evaluation of CCMMs often relies on the availability of respective emission factors (EFs). However, their uncertainty is typically larger than the difference between EFs representing the reference level emissions and those expected after CCMM implementation; in other words, the predicted impact of the intervention is often smaller than the associated uncertainty. Notably, this uncertainty is largely driven by spatial and temporal variability in emissions rather than measurement error, meaning that the main cause of high uncertainty is the limited number of observations used to derive EFs. Another shortcoming of EFs is that they cannot adequately capture the temporal dynamics of soil carbon accumulation or variability in GHG emissions following afforestation or rewetting interventions.

Continuous efforts are required to shift from using fixed EFs towards temporally and spatially explicit methods for estimating GHG emissions, considering inter- and intra-annual variation in factors affecting GHG emissions. Instead of relying on meta-analyses that average an agglomeration of published EFs, it is necessary to perform analyses using raw data from appropriate local studies. These analyses should result in dynamic and site-specific emission forecasting solutions that predict emissions based on local and regional meteorological conditions and other local GHG emission-related factors. These factors include, but are not limited to, soil properties, the water table, vegetation, and historical management practices (Meyer et al., 2013; Lohila et al., 2007; Mäkiranta et al., 2007). Such an approach can better enable the prediction of reliable and more robust spatially and temporally explicit emissions. To facilitate such analyses, and to maximize collective efforts in ensuring accurate, effective, and balanced planning, implementation, monitoring, and the continuous development of CCMMs, open science should be promoted to encourage the publication of raw data from studies.

To ensure the applicability of the developed GHG evaluation and projection methods, it is crucial to provide spatially and temporally explicit input data. The data should be based on remote sensing and accompanied by concurrent ground truth measurements for continuous validation and method enhancement (e.g. Ghezelayagh et al. 2024)). In addition to input data and GHG emission models, the integrity of decision support tools is equally vital. These tools are necessary for policymakers and land managers to plan and execute CCMMs in a balanced manner, selecting appropriately-scaled areas to achieve optimal climate change mitigation effects while considering both the mitigation potentials and associated risks.

Recognizing that each intervention carries inherent risks regarding desired outcomes, solutions are needed to monitor the impact of interventions and to be able to rapidly adjust implementation practices. Resources must be allocated not only for the initial implementation of CCMMs but also for their ongoing maintenance and climate impact monitoring to ensure that the projected GHG emission reductions or carbon sequestration are achieved Lack of proper mechanisms for monitoring rewetting success is worrisome due to the efficiency and uncertainty of rewetting implementation (Bonn et al., 2014), especially if expected credits are sold ex-ante (Günther et al., 2018) rather than based on actual, measured and independently verified GHG emission reductions and/or carbon removals (Palmer and Filoso, 2009). Hasty actions or 'greenwashing' (Polonsky et al.,

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2010) can accelerate environmental degradation (Palmer and Filoso, 2009), and distract attention from more necessary and efficient CCMMs addressing the energy sector (Baldocchi and Penuelas, 2019). Furthermore, rewetting and afforestation must directly address natural GHG emissions from peatlands. As implied by Dunn & Freeman (2011), when accounting for GHG emissions from CCMMs, the role of all peatlands must be considered to distinguish natural and anthropogenic global warming impacts (Huang et al., 2013; Kitson and Bell, 2020). Monitoring CCMMs can be performed with both on-site measurements (Günther et al., 2018) (e.g. GHG emissions, soil carbon stock changes, hydrological monitoring (Maier et al., 2022)), and remote sensing, as demonstrated, e.g. by (Ghezelayagh et al., 2024).

Given that the biota response to changes in the water table can take decades or centuries, consistent efforts must be undertaken to continuously assess the success of rewetting impacts (Kitson and Bell, 2020). Furthermore, it is essential to ensure that the GHG emission impact achieved by CCMMs is accurately reflected in GHG inventories. At present, various initiatives aimed at mitigating climate change, such as interventions introduced by the Common Agricultural Policy, carbon farming and emissions trading, are not properly captured in the inventories (Dunn and Freeman, 2011). For instance, despite often being promoted as an effective CCMM, rewetting is rarely implemented or sufficiently reported in GHG inventories. Out of the 27 EU member states, 21 have reported the presence of organic soils, but only 3 have reported GHG emissions related to rewetting. Latvia alone has reported around 70% of the total rewetted area (European Environment Agency, 2023) (Figure 5:).

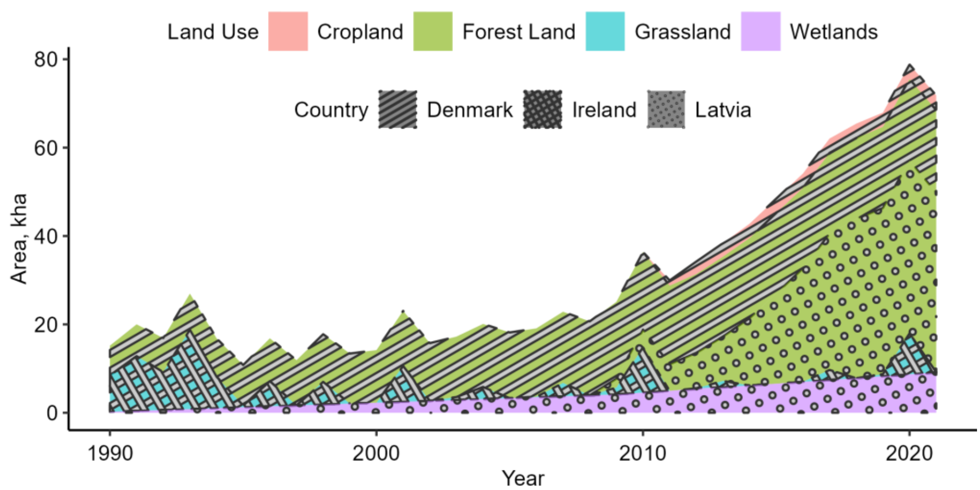

Figure 5: Reported area of rewetted lands in European Union (EU) greenhouse gas inventories. Organic soils are reported in 21 EU member states; however, rewetting is reported by only 3 countries. Most of the rewetted areas are classified as forest land, with approximately 70% reported by Latvia.

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7 Conclusions

Afforestation and rewetting are not mutually exclusive, but rather complementary measures. These measures do not compete with each other, as they have different objectives and are designed to target distinct land use types and promote divergent, but mutually beneficial, outcomes. Prioritizing rapid-gain measures while piloting rewetting where hydrology and native ecosystem can be restored, offers boreal and temperate peatland managers a phased, risk-managed mitigation pathway.

Net annual carbon sequestration, however, is necessary for LULUCF to fulfil its GHG offsetting role. Climate change mitigation measures (CCMMs) with significant rapid impacts on the net annual carbon flux are crucial for meeting the 2030 and 2050 climate goals, while the sustainability of carbon sequestration and GHG emission reductions is important in the long term and emphasizes the avoidance of future emissions. Neither are guaranteed by rewetting, whereas they are more predictable under afforestation. The main challenge for CCMM is achieving CO_2 sequestration and GHG emission reduction targets while managing risks. CCMMs must rely on accurate forecasting and accounting of potential failures resulting from implementation. Poorly planned measures which lack scientific support can have counterproductive effects, undermining climate goals and constraining economic activity. It is thus advisable to rely on CCMMs that can more reliably provide increased rates of carbon sequestration and emission reductions over the relevant period of interest.

Afforestation with continued drainage is effective in highly degraded former peatlands where the organic soil no longer exhibits peat characteristics or has elevated pH and enriched nutrients due to past fertilization. Afforestation in these areas reduces GHG emissions and ensures rapid CO_2 sequestration in living biomass and harvested wood products (HWPs), turning them into net greenhouse gas sinks. Emissions from drained forest soils are comparatively stable and carbon sequestration in biomass and harvested wood products is both manageable and desirable. The forest management cycle is comparably short and adjustable (Ménard et al., 2023), and long-term experience with forestry provides reliable forecasts of carbon sequestration in living biomass (Doelman et al., 2020) and HWPs. This allows us to predict the impact of afforestation more accurately and reliably from the initial years and onward through subsequent forest management cycles. Therefore, the afforestation of drained organic soils offers predictable outcomes (Dunn and Freeman, 2011). The most significant long-term benefit of afforestation is the avoided emissions associated with the use of HWPs through substitution effects. The risk of HWPs carbon sink not fully offsetting soil carbon losses can be mitigated with strategic wood utilization – i.e., the targeted promotion of *long-lived* HWPs. Afforestation thus offers predictable and reliable outcomes, making it suitable for achieving both short- and long-term climate goals.

Rewetting, aimed at achieving ecological benefits and reducing long-term soil carbon loss, is better suited to moderately degraded peatlands where peat characteristics have not been irreversibly altered, the soil continues to exhibit a high carbon stock, and restoration remains possible. The climate change mitigation impact of rewetting is both less effective and difficult to predict in both the short- and long-term due to fluctuating groundwater levels, uncertain biota development and the changing climate. Rewetting has been shown to be more effective in temperate zone compared to boreal zones, where scientific evidence on its effectiveness is still lacking. High variability in CH_4 emissions and unexpected CO_2 and N_2O emissions further

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complicate reliable estimates. Therefore, considering the high reliance on long-term predictions of soil carbon stocks and CH_4 emissions, and acknowledging that CH_4 emissions from wet soils are highly uncertain and poorly understood (Gios et al., 2024; Kitson and Bell, 2020), with no guarantee of future carbon removals (Gios et al., 2024; Günther et al., 2018; Bacon et al., 2017), the climate expectations for rewetting are ambiguous. For these reasons, rewetting is an ineffective CCMM measure in the short term, and optimistic long-term projections of rewetting's climate benefits may fall short. Despite limited experience with implementation, rewetting aims to extensively change existing land-use practices based on insufficiently substantiated expectations about its climate benefits. Inefficiency and risks associated with rewetting increase when inappropriate areas are chosen for implementation. Unless these issues can be reliably addressed, overreliance on rewetting carries the risk of limiting economic activity and promoting unintended climate consequences. Overlooking these factors may undermine mitigation outcomes and impose unnecessary economic costs.

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Appendix A

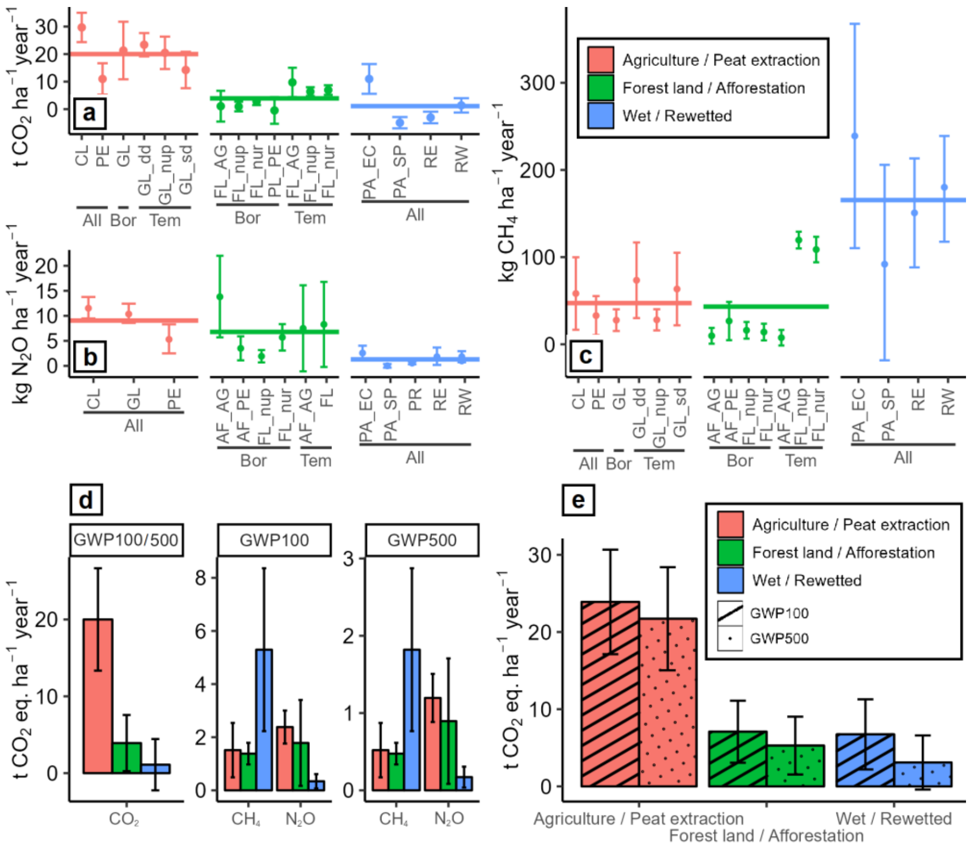

Figure A1: Emission factors characterizing soil GHG emissions from agricultural lands, peat extraction sites, afforested or rewetted lands (a, b, c), and the expected climate impact in the corresponding scenarios (d, e). Both the means (horisontal lines) and their uncertainties (error bars) are calculated by assigning equal weight to the underlying emission factor values and their associated 95% confidence intervals (Table S1). The uncertainties of the summed emissions, expressed in CO_2 equivalents, were derived by propagating the uncertainties from the underlying EFs using the square root of the summed squares method. CO_2 emissions include dissolved organic carbon (DOC)-related off-site emissions. Methane (CH_4) emissions from drained soils include emissions from drainage ditches, according to IPCC guidelines (Hiraishi et al., 2013). CO_2 rewetting (RW) emissions may be underestimated because the EFs used represent sites with an annual mean water table above 25 cm. In addition, soil carbon stock loss due to removal of the agriculturally-affected topsoil is not accounted for. Therefore, these RW EFs do not account for the emissions from unsuccessful RW efforts and soil carbon stock loss resulting from Sphagnum paludiculture practices (Bianchi et al., 2021). Abbreviations used: FL - drained forestry sites; nup - nutrient-poor sites; nur – nutrient-rich sites; AF_AG - afforested sites previously used for agriculture; AF_PE - afforested sites previously used for peat extraction; PR – pristine wetlands; RW – all available rewetted sites; RE – restored sites; PA_SP – paludiculture with Shagnum; PA_EC – paludiculture with emergent crops; Cl – cropland; GL – grassland; GL_dd – deep-drained grassland; GL_sd – shallow-draned grassland; PE – peat extraction sites; All – all available sites in boreal and temperate peatlands, Bor – boreal peatlands; Tem – temperate peatlands. GWP100 and GWP500 – global warming potentials over 100 and 500 year timeframes are used, based on Neubauer and Megonigal (2015).

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Table A1: Soil greenhouse gas emission factors. The table presents data used to compare soil greenhouse gas emissions from rewetted and afforested agricultural lands.

Efflux	Source	Region	Land-use	Soil nutrient status	t ha^{-1} yr^{-1}	CI lower	CI upper	Source
			Agriculture / Peat extraction					
CH_4	On-site	Boreal and temperate	Cropland	Unspecified	0.0000	-0.0027	0.0027	Hiraishi et al. 2014
CH_4	On-site	Boreal	Grassland	Unspecified	0.0013	-0.0015	0.0043	Hiraishi et al. 2014
CH_4	On-site	Temperate	Grassland	Nutrient-poor	0.0017	0.0007	0.0028	Hiraishi et al. 2014
CH_4	On-site	Temperate	Grassland	Nutrient-rich	0.015	0.002	0.028	Hiraishi et al. 2014
CH_4	On-site	Temperate	Grassland	Nutrient-rich	0.037	-0.003	0.077	Hiraishi et al. 2014
CH_4	On-site	Boreal and temperate	Peat extraction	Unspecified	0.006	0.002	0.010	Hiraishi et al. 2014
CO_2	On-site	Boreal and temperate	Cropland	Unspecified	28.97	23.83	34.47	Hiraishi et al. 2014
CO_2	On-site	Boreal	Grassland	Unspecified	20.90	10.63	31.53	Hiraishi et al. 2014
CO_2	On-site	Temperate	Grassland	Nutrient-poor	19.43	13.57	25.30	Hiraishi et al. 2014
CO_2	On-site	Temperate	Grassland	Nutrient-rich	22.37	18.33	26.77	Hiraishi et al. 2014
CO_2	On-site	Temperate	Grassland	Nutrient-rich	13.20	6.60	19.80	Hiraishi et al. 2014
CO_2	On-site	Boreal and temperate	Peat extraction	Unspecified	10.27	4.03	15.40	Hiraishi et al. 2014
N_2O	On-site	Europe	Cropland	Unspecified	0.012	0.009	0.014	Lin et al. 2022
N_2O	On-site	Europe	Grassland	Unspecified	0.010	0.009	0.012	Lin et al. 2022
N_2O	On-site	Europe	Peat extraction	Unspecified	0.005	0.002	0.008	Lin et al. 2022
			Forest land / Afforestation					
CH_4	On-site	Boreal	Forest land	Nutrient-rich	0.0032	-0.0006	0.0069	Jauhiainen et al. 2023
CH_4	On-site	Boreal	Forest land	Nutrient-poor	0.0052	0.0014	0.0089	Jauhiainen et al. 2023
CH_4	On-site	Temperate	Forest land	Nutrient-rich	0.11	0.09	0.12	Jauhiainen et al. 2023
CH_4	On-site	Temperate	Forest land	Nutrient-poor	0.12	0.11	0.13	Jauhiainen et al. 2023
CH_4	On-site	Boreal	Afforested agriculture land	Unspecified	-0.0011	-0.0033	0.0011	Jauhiainen et al. 2023
CH_4	On-site	Boreal	Afforested peat extraction site	Unspecified	-0.0004	-0.0006	-0.0003	Jauhiainen et al. 2023
CH_4	On-site	Temperate	Afforested agriculture land	Unspecified	-0.0033	-0.0049	-0.0018	Jauhiainen et al. 2023
CO_2	On-site	Boreal	Forest land	Nutrient-rich	2.42	1.09	3.75	Jauhiainen et al. 2023
CO_2	On-site	Boreal	Forest land	Nutrient-poor	0.56	-1.18	2.30	Jauhiainen et al. 2023
CO_2	On-site	Temperate	Forest land	Nutrient-rich	5.91	4.23	7.60	Jauhiainen et al. 2023
CO_2	On-site	Temperate	Forest land	Nutrient-poor	5.35	3.82	6.88	Jauhiainen et al. 2023
CO_2	On-site	Boreal	Afforested agriculture land	Unspecified	0.68	-4.91	6.27	Jauhiainen et al. 2023
CO_2	On-site	Boreal	Afforested peat extraction site	Unspecified	-0.86	-5.71	3.99	Jauhiainen et al. 2023
CO_2	On-site	Temperate	Afforested agriculture land	Unspecified	9.32	4.03	14.62	Jauhiainen et al. 2023

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N_2O	On-site	Boreal	Forest land	Nutrient-rich	0.0057	0.0031	0.0083	Jauhiainen et al. 2023
N_2O	On-site	Boreal	Forest land	Nutrient-poor	0.0019	0.0007	0.0032	Jauhiainen et al. 2023
N_2O	On-site	Temperate	Forest land	Unspecified	0.0083	-0.0002	0.0168	Jauhiainen et al. 2023
N_2O	On-site	Boreal	Afforested agriculture land	Unspecified	0.014	0.006	0.022	Jauhiainen et al. 2023
N_2O	On-site	Boreal	Afforested peat extraction site	Unspecified	0.0035	0.0011	0.0059	Jauhiainen et al. 2023
N_2O	On-site	Temperate	Afforested agriculture land	Unspecified	0.0075	-0.0011	0.0161	Jauhiainen et al. 2023
				Wet / Rewetted				
CH_4	On-site	Boreal and temperate	Restored	Unspecified	0.15	0.09	0.21	Bianchi et al. 2021
CH_4	On-site	Boreal and temperate	Sphagnum paludiculture	Unspecified	0.09	-0.02	0.21	Bianchi et al. 2021
CH_4	On-site	Boreal and temperate	Emergent crops paludiculture	Unspecified	0.24	0.11	0.37	Bianchi et al. 2021
CH_4	On-site	Boreal and temperate	Rewetted	Unspecified	0.18	0.12	0.24	Bianchi et al. 2021
CO_2	On-site	Boreal and temperate	Restoration	Unspecified	-3.50	-5.60	-1.40	Bianchi et al. 2021
CO_2	On-site	Boreal and temperate	Sphagnum paludiculture	Unspecified	-5.40	-7.40	-3.30	Bianchi et al. 2021
CO_2	On-site	Boreal and temperate	Emergent crops paludiculture	Unspecified	10.50	5.20	16.00	Bianchi et al. 2021
CO_2	On-site	Boreal and temperate	Rewetted	Unspecified	0.90	3.50	3.50	Bianchi et al. 2021
N_2O	On-site	Europe	Pristine peatland	Unspecified	0.001	0.000	0.001	Lin et al. 2022
N_2O	On-site	Europe	Rewetted	Unspecified	0.001	0.001	0.001	Lin et al. 2022
N_2O	On-site	Boreal and temperate	Restoration	Unspecified	0.0018	0.0002	0.0037	Bianchi et al. 2021
N_2O	On-site	Boreal and temperate	Sphagnum paludiculture	Unspecified	0.0000	-0.0004	0.0004	Bianchi et al. 2021
N_2O	On-site	Boreal and temperate	Emergent crops paludiculture	Unspecified	0.0026	0.0011	0.0040	Bianchi et al. 2021
N_2O	On-site	Boreal and temperate	Rewetted	Unspecified	0.0018	0.0011	0.0029	Bianchi et al. 2021
				CH_4 from drainage ditches and off-site CO_2				
CH_4	Ditch	Boreal and temperate	Grassland	Unspecified	0.026	0.014	0.038	Hiraishi et al. 2014
CH_4	Ditch	Boreal and temperate	Grassland and cropland	Unspecified	0.058	0.017	0.100	Hiraishi et al. 2014
CH_4	Ditch	Boreal and temperate	Peat extraction	Unspecified	0.027	0.005	0.049	Hiraishi et al. 2014
CH_4	Ditch	Boreal and temperate	Forest land	Unspecified	0.011	0.002	0.020	Hiraishi et al. 2014
DOC	Off-site	Boreal	Drained	Unspecified	0.40	0.23	0.63	Hiraishi et al. 2014
DOC	Off-site	Temperate	Drained	Unspecified	1.0230	0.6270	1.5180	Hiraishi et al. 2014
DOC	Off-site	Boreal	Undrained	Unspecified	0.26	0.20	0.36	Hiraishi et al. 2014
DOC	Off-site	Temperate	Undrained	Unspecified	0.69	0.56	0.86	Hiraishi et al. 2014

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Appendix B: Emission factor synthesis methodology

To present the expected soil greenhouse gas emissions (Figure 3, Figure A1), we identified the most recent systematic reviews and synthesis studies relevant to the scope of this Perspective. Only emission factors (EF) representative of temperate and boreal peatlands and the land-use categories considered in this study were included (Table A1). Specifically, emission factors for forest lands and afforestation were obtained from Jauhiainen et al. (2023); rewetted agricultural soils from Bianchi et al. (2021); nitrous oxide (N_2O) emissions from rewetted and pristine peatlands from Lin et al. (2022); and emission factors for agricultural lands, peat extraction sites, methane emissions from drainage ditches, and dissolved organic carbon-related emissions from Hiraishi et al. (2014). Emission factors pooled were harmonized by recalculating them to common units. Mean emission factors were calculated by assigning equal weight to the underlying published emission factor values (Table A1), while uncertainty was estimated by propagating the reported 95% confidence intervals using the root-sum-of-squares method. CO_2 equivalents were calculated using the 100-year global warming potentials (GWP) for CH_4 and N_2O (Neubauer and Megonigal, 2015).

Data availability

This Perspective is based entirely on previously published literature cited in the references. No new data were collected, and all information discussed is derived from published sources.

Author contributions

Aldis Butlers wrote the initial draft, Ieva Līcīte and Arta Bārdule contributed to subsequent improvements, with David Ellison providing critical review; all authors have read and approved the final version.

Competing interests

The authors declare no conflicts of interest relating to this manuscript.

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