Active afforestation of drained peatlands is not a viable option under the EU Nature Restoration Law

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Executive Summary

Several EU Member States argue that active afforestation of degraded peatlands should be recognized as a restoration measure under the Nature Restoration Law (NRL). In this perspective paper, we discuss the scientific evidence on the greenhouse gas fluxes of peatlands under forestry and its limitations, uncertainties and evidence gaps. In our opinion:

- Afforestation of drained peatlands, while maintaining their drained state, is not equivalent to ecosystem restoration. This approach will not restore the peatland ecosystem's flora, fauna, and functions.
- Currently, there is insufficient evidence to support the long-term climate change mitigation benefits of active afforestation of drained peatlands.
- Most studies only focus on the short-term gains in standing biomass and rarely explore the full life cycle emissions associated with afforestation of drained peatlands. Thus, it is unclear whether the CO_2 sequestration of a forest on drained peatland can offset the carbon loss from the peat over the long term.
- In some ecosystems, such as abandoned or certain cutaway peatlands, afforestation may provide short-term benefits for climate change mitigation compared to taking no action. However, this approach violates the concept of sustainability by sacrificing the most space-effective carbon store of the terrestrial biosphere, the long-term peat store, for a shorter-term, less space-effective, and more vulnerable carbon store, namely tree biomass.
- Consequently, active afforestation of drained peatlands is not a viable option for climate mitigation under the EU Nature Restoration Law.
- To restore degraded peatlands, hydrological conditions must first be improved, primarily through rewetting.

1. Introduction

The EU Nature Restoration Law is critical in reaching climate mitigation targets, as the most recent IPCC report very clearly shows (IPCC AR6 SYR 2023). The carbon dioxide (CO_2) sinks necessary to reach climate neutrality and then net cooling during the second half of this century will, for the most part, rely on the land use sector (LULUCF). Sinks should not be used to compensate for avoidable sources and emission reduction remains the utmost priority.

Several EU member states pursue the recognition of active afforestation of drained and degraded peatlands (without rewetting) as a measure under the Nature Restoration Law (NRL). This is, however, problematic from a scientific perspective. Firstly, afforestation of drained peatlands, while keeping them drained, will not restore the peatland ecosystem with its flora, fauna and functions. Secondly, as long as a peatland remains drained, it will degrade further, carbon stored in the peat is lost to the atmosphere, and downstream systems may be severely polluted with nutrients and dissolved organic matter (Zak & McInnes 2022). Typically, much more carbon is stored in the peat than in the forest biomass (Tanneberger et al. 2021), and long-term losses from the drained soil will likely be larger than storage in the forest biomass (Dunn & Freeman 2011), and the biomass carbon will be lost back to the atmosphere if a forest is used for production purposes.

Presently, there is little evidence to support the claim that afforestation on drained peatlands could be beneficial for climate change mitigation in the long-term. In most cases, CO_2 release from peat soil degradation will likely exceed carbon sequestration in forest biomass when considering full growth cycles, as was also concluded by IPCC in the 2013 Wetlands Supplement (IPCC 2014). In contrast, ecosystem-scale flux measurements show that rewetting/restoration[1] of forestry-drained peatlands can reduce soil CO_2 emissions and even restore the CO_2 sink function within a few years/decades (Hambley et al. 2019).

Some recent studies suggesting afforestation as the best possible restoration measure (*e.g.*, Butlers et al. 2021, Butlers et al. 2022a/b, Samariks et al. 2023) either did not measure all relevant greenhouse gases and carbon fluxes or only covered very short time periods. Potential lateral losses of C as dissolved organic or inorganic carbon and as particulate organic carbon are rarely considered but can be substantial (Billett et al. 2004). To provide reliable data, measurement periods should cover the entire land use cycle—from site preparation to sowing or planting, growth of the biomass, thinning or ditch cleaning, through to harvest, the fate of the biomass (whether used for long-lived products or not) and the fallow time before renewed site preparation. For cropping agriculture, this cycle commonly takes a single year, in forestry it takes much longer. Longer, comprehensive greenhouse gas monitoring studies are currently only available from the boreal region and even here, the authors call for longer-term studies that include the entire life cycle (*e.g.*, Bjarnadottir et al. 2021). Such studies do not exist to date and so we can only approach the true climate balance of peatland forestry by using space-for-time substitution and stitching together studies that cover different stages of the forestry life cycle.

Given the lack of conclusive evidence, it would be wrong to accept active afforestation of drained peatlands as a viable option for climate mitigation under the NRL. This is all the more true given additional negative effects that may arise from peatland forestry: Forestry on drained peatlands further lowers the water table by interception and increased transpiration of the trees, is more susceptible to wildfires, which are becoming more frequent and severe due to climate change and droughts in the boreal zone leading to increased carbon losses (*e.g.*, Zhao et al. 2021, Zheng et al. 2023, Liu et al. 2023), and also negatively impacts water storage capacity, water quality, and nutrient runoff, leading to greater variations in stream flow and water quality for downstream aquatic ecosystems (*e.g.*, Evans et al. 2016, Flynn et al. 2022).

In the following, we discuss the role of peatlands in relation to the climate with respect to forestry-drained peatlands in particular.

2. Peatlands and climate

Plants absorb CO_2 and store the carbon in their biomass. When they die, they are decomposed and the CO_2 is released again. In intact peatlands—called mires—water saturation of the soil effectively excludes oxygen, inhibiting the full decomposition of the dead plant material, which then accumulates as peat. In this way, peatlands have sequestered huge amounts of carbon over thousands of years. Globally, peatlands store approximately 600 Gt of carbon (Yu et al. 2010), which is more than is contained in global forest above-ground biomass (Santoro et al. 2021), and have cooled the planet by approximately 0.6°C over the past 10,000 years (Frolking & Roulet 2007, Joosten et al. 2016). Forests and peatlands are fundamentally different in terms of C cycling over

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[1] *Rewetting* and *restoration* are often used interchangeably but they are not. *Rewetting* describes the deliberate action of raising the water table on drained soils to re-establish water saturated conditions. In contrast, *restoration* refers to the full re-establishment of all ecosystem functions which cannot be done directly but only be aimed at by taking facilitating measures like, for instance, rewetting, removing degraded topsoil, re-introducing mire-typical vegetation, etc.

time, in that pristine mature forests are generally in balance, whereas peatlands continue to accumulate carbon year after year.

To understand the climate impact of peatlands, it is necessary to briefly review the relevant processes. While intact peatlands (mires) sequester carbon from the atmosphere, incomplete decomposition under water-saturated oxygen-free conditions results in the production of methane (CH_4). The amount of CH_4 released from intact, wet peatlands varies strongly depending on environmental conditions like pH, temperature and dominant vegetation (*e.g.*, Lai 2009). Methane is a short-lived greenhouse gas. On average, it stays in the atmosphere for less than 12 years. If there is a steady emission of CH_4, a dynamic equilibrium will establish over time in which in a certain year exactly as much CH_4 disappears from the atmosphere as is added, and the CH_4 concentration in the atmosphere and the climate impact do not increase any further (Frolking & Roulet 2007). Natural, undrained peatlands almost always release CH_4, but the net uptake of CO_2 overcompensates the CH_4 losses in the long-term. In mires, *i.e.*, wet peat-forming peatlands, formation and emission of nitrous oxide (N_2O, a potent greenhouse gas) is negligible.

When peatlands are drained, the upper soil layers are no longer water saturated, oxygen enters the peat, and decomposition of organic matter becomes much more efficient, leading to mineralisation of the peat and, thus, high CO_2 (Ojanen et al. 2010, Jovani-Sancho et al. 2018) and N_2O emissions (IPCC 2014, Klemedtsson et al. 2005, Leppelt et al. 2014, Minkkinen et al. 2020). In contrast, CH_4 production and emissions decrease because of water table drawdown, while drainage ditches may remain a major source of CH_4 emissions (Minkkinen et al. 1997, Köhn et al. 2021, Rissanen et al. 2023). Thus, draining undisturbed peatlands reduces soil CH_4 emissions but increases the soil CO_2 and N_2O emissions. In the case of forestry, drainage also increases tree stand carbon stock, until the stand is cut. This may lead to short-term cooling, but in most cases, the long-term effect will be warming (Laine et al. 1996, Ojanen & Minkkinen 2020).

In order to determine the climate-effectiveness of rewetting drained peatlands, we need to compare CO_2, CH_4, and N_2O emissions and lateral losses of C and N both in the drained and the rewetted situations. Rewetting of drained peatlands is always a choice between continued emissions of (a) long-lived GHGs (CO_2 and N_2O) and (b) a short-lived GHG (CH_4). In the short term, rewetting will cause a warming impact because of increased CH_4 emissions, but in the long-term (decades to centuries) the result is cooling (Ojanen and Minkkinen 2020, Wilson et al. 2016/2022, Günther et al. 2020). Especially for cutover peat bogs (Rochefort et al. 2003, González & Rochefort 2014) but also after top-soil removal on formerly drained grassland on bog peat (Huth et al. 2022) it has been shown that re-introduction of mire-typical vegetation can speed up the process of restoration including a strong reduction of total GHG emissions after rewetting.

3. Forestry on peatlands

Peatland forestry is concentrated in the boreal zone, but also occurs across the temperate climate zone. It is common in many European countries, mainly in the north (*i.e.*, Finland, Sweden, and Norway), but is also of national importance in the Baltic countries, the United Kingdom, Ireland, Poland and Germany (see Figure 1, data for non-EU countries are not included). Peatlands used for forestry are typically drained, which leads to simultaneously increasing CO_2 emissions through peat decomposition (see above) and CO_2 sequestration through the growing tree stand.

4. Available evidence regarding peatland forestry and climate

Although soil CO_2 emissions increase after drainage, several studies on drained boreal peatland forests, made with micrometeorological or combined chamber-efflux-litter-production-methods, suggest that carbon sequestration in the tree biomass can exceed the carbon loss from the decomposition of the peat (Lindroth et al. 2007, Meyer et al. 2013, Ojanen et al. 2013; Hommeltenberg et al. 2014, Uri et al. 2017, Minkkinen et al. 2018, Bjarnadottir et al., 2021). In most cases, however, soil C stocks decrease over time, which is the deciding factor when whole rotation climate impacts are considered. Nutrient-poor sites in the boreal zone may accumulate C in soils (Ojanen et al. 2013), but in the absence of a high water table, the fate of this C is unclear over a production cycle.

The most common way to measure greenhouse gas fluxes in treeless peatlands has been to place airtight chambers on the soil and to measure the change in the concentration of gases inside the chamber. This commonly applied chamber technique cannot be used in a forest stand as the trees do not fit inside the chambers. Therefore, the soil carbon balance has been estimated by subtracting measured litter production from heterotrophic soil respiration (*e.g.*, Ojanen et al. 2012, 2013, Jovani-Sancho et al. 2021, Uri et al. 2017) where the latter has been measured from trenched plots in which plants and tree roots have been killed. Simply placing chambers on the forest soil will not provide reliable measurements of fluxes from soil degradation, because the roots of the trees emit CO_2 as well (*i.e.*, autotrophic soil respiration). Intricate chamber set-ups are required to distinguish between emissions from the soil (*i.e.*, heterotrophic soil respiration) and from the living tree roots (*i.e.*, autotrophic respiration) (Mäkiranta *et al.* 2008, Hermans et al. 2022).

The eddy covariance technique (EC), which uses highly sophisticated, fast measuring gas analysers, requires large flat and homogeneous areas that are rarely available also because forestry areas on peatlands are often organised in fairly small blocks. EC is the standard method for ecosystem-level measurements. The technique has a typical accuracy of about ±20% (SEM) and is technically challenging. The method also allows for the estimation of the soil C sink/source by subtracting the biomass increment from the measured net ecosystem exchange. This can be done by biomass measurements and modelling, which needs accuracy, but is doable. Other soil C balance estimation methods include the estimation of soil subsidence through pollen or C isotope profiles or by consecutive thickness measurements (Minkkinen et al. 1999, Hooijer et al., 2012, Simola et al. 2012, Sloan et al., 2019). These integrate longer time periods. Getting accurate estimates is, thus, challenging.

The above-mentioned studies consider forestry on drained peatlands, which is based on natural tree stands in the boreal zone. In the temperate zone, sites have more often been drained for agriculture or peat extraction and only later been afforested. Most of the studies do not describe the situation after afforestation of agricultural fields or cutover peatlands, but this difference in soil management history may lead to different outcomes. In addition, the above-mentioned gas exchange studies only give a temporary GHG balance for the study period. ***They do not consider the whole forestry cycle, which includes harvesting of the wood (i.e., the removal of sequestered biomass C), decomposition of wood products, and the time needed for stand regeneration. Harvested sites, especially clear-cut sites are large C sources*** (Korkiakoski *et al.* 2019; Korkiakoski *et al.* 2023), until a new stand has been regenerated. In addition, only a small part of wood products are long-lived, most of the C in wood products is lost to the atmosphere in a few years after cuttings (Soimakallio et al. 2016).

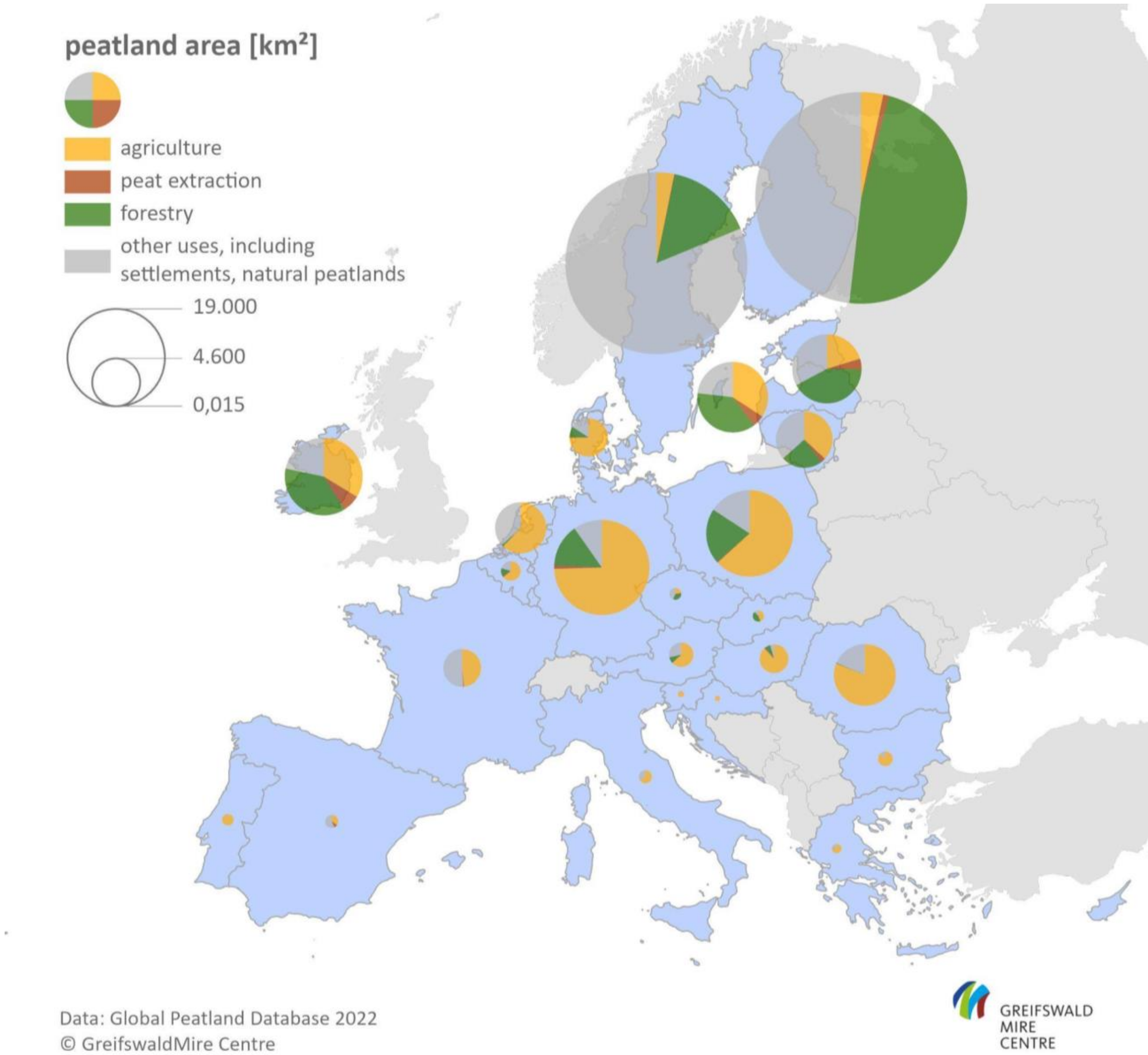

Figure 1: Areal share of peatlands under agriculture, peat extraction, forestry, and other uses in countries of the European Union. Colours refer to different land use types, the size of the circles reflects total peatland area. Map prepared by Cosima Tegetmeyer.

One recent, relatively comprehensive and well-measured study from Iceland (Bjarnadottir et al. 2021) showed no negative effects of peatland forestry compared to rewetted or wet peatlands. The study area, a poorly drained site, was afforested with a very productive species (Black cottonwood, *Populus trichocarpa*). According to the authors, only further long-term studies and life-cycle assessments will show whether forestry on drained peatlands can really be more climate friendly than wet and healthy peatlands. A recent meta-analysis on the climate effects of forestry on *shallow* organic soils (<40-50cm peat depth) in Scotland showed no negative climate effect (Vanguelova *et al.* 2018). However, meta-analyses on the effects of forestry on *deep* peat soils in the temperate climate region showed considerable net emissions of CO_2 to the atmosphere (Hommeltenberg et al. 2014, Jovani-Sancho *et al.* 2021). The latter finding confirms the emission factors derived in the 2013 IPCC Wetland Supplement (IPCC 2014). The considerably lower figures for carbon loss from the soil in Hermans et al. (2022) show that there can be strong variation across sites suggesting that more research on the matter is needed. With respect to the harvesting stage of peatland forestry, it was shown that selective cutting instead of clear-cutting can lower GHG emissions in a forestry drained peatland in the boreal climate zone (Korkiakoski *et al.* 2023). Although the site with partial harvest transformed into a CO_2 sink five years after harvest, peat decomposition continued, releasing almost the same amount of carbon into the atmosphere as was fixed by the trees. Most studies in drained peatland forests show similar results: the ecosystem may be a C sink, whereas the soil is a C source. Therefore, production forestry, where biomass C is harvested and rapidly lost back to the atmosphere (Soimakallio et al. 2016), will likely result in net C losses in the long run. Thus, ***none of the studies discussed above provides a basis to include active afforestation on drained peatlands, especially if managed for production forestry, as a viable option under the NRL***.

Some recent studies from Latvia do seem to support the idea that afforestation of drained peatlands could be better for the climate than rewetting. However, these studies are inconclusive, have major flaws and biases and cannot be verified and validated because the methods used are error prone and descriptions often lack clarity. For instance, Samariks et al. (2023) claim that they show that afforestation of peat extraction sites can result in net carbon removals. However, they did not measure all elements of the carbon cycle. Using chamber measurements, they failed to clearly distinguish between soil emissions and emissions from tree roots. Instead of analysing, they simply *assumed* that the soil fluxes made up less than half of the measured total flux, independent of changes in management or site conditions, which is unrealistic. Moreover, the appropriate comparison would be with a rewetted peat extraction site. The study of Bārdule et al. (2022) suggests that emissions from wet peatlands are not lower than in drained peatlands. However, they measured only once per month over a period of only four months, during only one vegetation period. Their experimental set-up allowed only the CO_2 flux going out of the system (soil and litter degradation plus plant respiration) to be measured, but not the sequestration of CO_2 from the atmosphere during photosynthesis. Moreover, they neglected to account for the carbon export from the drained sites. ***Results of studies that only address parts of the GHG exchange in afforested peatlands are not appropriate to draw conclusions on whether afforestation of drained peatlands is the best choice for the climate.***

In another example, Butlers et al. (2021) report larger N_2O and CH_4 emissions from 'naturally wet' sites than from 'drained' forests. These findings are not surprising considering that their 'naturally wet' site was only slightly less dry (water tables more than 60 cm below the soil surface in summer!). Again, a full GHG balance can only be assessed when CO_2 exchange is included as well. The same authors claim to have shown that CO_2 emissions from 'naturally wet', nutrient-rich organic forest soils can be larger than those from drained sites (Butlers et al. 2022a). However, they again used a technique that fails to depict net-CO_2 exchange appropriately, as it excludes photosynthesis by the ground vegetation and lacks the quantification of CO_2 release from the tree roots. The authors state that the "study results demonstrate that drainage does not have significant effect on CO_2 emissions", a conclusion not supported by their data. ***Without inclusion of the contribution of the trees and without a full life cycle assessment, no sensible conclusions on the climate effect of wet vs. drained forested peatlands can be drawn.***

Butlers et al. (2022a) attempt to get a better understanding of the whole GHG balance by looking at different stages of the harvest cycle and even including the input of litter. Again, the same error-prone methods are used. No distinction is made between root- and soil derived emissions in the measurements, but instead a regression equation is used that deems slightly more than half of the measured flux to be related to decomposition of litter and soil. The used equation presents a broad relationship that may be helpful to constrain large scale estimates, but it was not made to infer sitespecific flux values, as was stressed by the original authors (Bond-Lamberty et al. 2004). Again, the conclusions are based on a very short time series of measurements. This falls far short of a full life cycle assessment that is essential to provide reliable data on the effects of forest growth on drained peatlands in comparison to the situation in rewetted or pristine peatlands. In addition, there were no measurements conducted in intact or rewetted peatlands to provide an appropriate baseline for comparison. Thus, ***the study results are unsuitable to support far reaching generalisations regarding afforestation of peatlands as viable options to achieve climate goals under the NRL***.

In addition to GHG exchange, also the change in albedo and the release of aerosols as well as the lateral exchange of carbon and nitrogen add to the total climate effect of ecosystems (Billett et al. 2010). Increased tree cover decreases albedo compared to a treeless mire (Lohila et al. 2010), which leads to local warming (Gao et al. 2014). In contrast, forests are large sources of biogenic volatile organic compounds (BVOCs) and thus may have a considerable cooling impact on the climate (Tunved et al. 2006). In the boreal zone, this impact is similar in magnitude, but opposite to that of albedo (Kalliokoski et al. 2020).

Most importantly, however, the felling of trees and the subsequent fate of the carbon sequestered in the wood needs to be considered (Ciais et al. 2008). As little as 50% of actual tree biomass may be extracted during harvest, the remainder is left to decompose on site and within a few years returns as CO_2 to the atmosphere (Leturq 2020; Korkiakoski *et al.* 2019). After the tree is felled, a fair amount of its carbon can be stored in wood products (there will always be some parts lost during production). Yet, a simple carbon balance does not tell the whole story; unlike the carbon stock in soil and peat, not everything made out of wood is climate neutral (Leturq 2020). As a rule, for a long-lasting product made out of 80 year old wood to be climate cooling, the wood should not be discarded and burnt for at least 40 years after harvest. A product made out of 40 year old wood would need to remain for at least 20 years after harvest (Guest et al. 2013; Galimshina et al. 2022). Long-lived harvested wood products are actually quite rare, and harvesting does reduce the amount of total carbon stored in the forest (Soimakallio et al. 2022). ***In assessing the GHG balance of peatland forestry, complete harvest cycles should be taken into account. Such data are simply absent at the moment.***

Since trees grow slowly, no measurements of full growth cycles are yet available and results spanning longer time periods are derived from the investigation of chronosequences. Certainly, more chronosequence work is needed, but measurements must be made over multiple years so that variations in weather and other environmental conditions can be integrated into the models. As Vanguelova et al. (2018) have expressed: “There is a clear need for long term studies using different planting ages (chronosequence studies) to ensure robust results when evaluating the impacts of afforestation and restocking on soil carbon stocks, as short-term impact studies are likely to provide misleading conclusions.”

Finally, it has been shown that peatland forestry on drained sites is more prone to wildfires (Kohlenberg *et al.* 2018), which will become more frequent and severe in times of climate change with more frequent and more intense droughts in the boreal zone (Walker et al. 2019). Boreal forests in North America have turned from a net sink to a net source of GHG in recent years (Zhao et al. 2021), primarily due to more frequent and more severe fires (Zheng et al. 2023). In addition to the carbon loss from burnt wood, substantial carbon losses from burnt and burning peat layers should be considered including the water-born carbon losses (Liu et al. 2023). The severity of peatland fires might also be high because in countries where the density of forest roads is relatively high (*e.g.*, in Finland), large drained peatland areas may usually still have lower density of roads compared to upland areas, making fires more difficult to be controlled. Having said that, Finland's land use sector seems to have gradually transitioned from being a CO_2 sink to a source already (Statistics Finland 2022b). Siljander et al. (2022) suggest that the fastest way to strengthen carbon sinks in Finland is to reduce logging and the Finnish nature panel recommends, among other things, the rewetting and restoring of wetlands and peatlands (Lång et al. 2022).

Aside from impacts to emissions, forestry on peatland may have negative impacts on water storage capacity, water quality and nutrients runoff, including loss of organic matter via fluvial pathways, which is subsequently mineralised and the carbon partially returned to the atmosphere (Evans et al 2016). It has to be mentioned, that also rewetting of drained peatlands can lead to considerable amounts of N and P leaching (*e.g.*, Koskinen et al. 2017) but nutrient loss will decrease once the system is biogeochemically stable again. The loss in water storage capacity due to the loss of pore space caused by drainage can manifest itself in greater variations in stream flow and water quality for downstream aquatic ecosystems (Flynn et al. 2022). Intense rainfall events are predicted to increase under climate warming, which can cause mid-term flooding leading to the die-back of trees caused by increased hydrological instability. ***Indeed, research to evaluate the trade-off values of wood production, carbon sequestration and emissions and water storage of natural, drained and rewetted peatlands is urgently required*** (Stachowicz et al. 2021).

5. Conclusion

The most recent IPCC report (IPCC AR6 SYR 2023) outlines in clear language: We have to get to grips with proper natural climate solutions since they are our only option to avoid the gravest consequences of climate change and global warming. Therefore, we need an effective Nature Restoration Law (NRL) in the EU. ***The many open questions and lack of evidence for overall climate benefits of active afforestation on peatlands prohibit its inclusion as a viable climate change mitigation measure in the NRL***. In addition, the NRL should foster true natural ecosystems wherever possible, and a forest that can only grow when the peat below the trees is drained does not comply with this requirement. ***Afforestation of drained peatlands is not restoration but afforestation***. ***We cannot restore a peatland ecosystem, its flora, its fauna, its functions, by afforestation. The only solution to restore a peatland ecosystem is rewetting.*** The reintroduction of natural mire vegetation can potentially speed up the restoration process. If trees belong to such an ecosystem, they will regenerate naturally.

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