

## Climate mitigation by peatland restoration – challenges and solutions

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### Background

#### What are peatlands?

Peatlands are ecosystems that have accumulated carbon in layers of water saturated organic soil called peat. Peatlands can be called wetlands, because the peat formation process requires wetness and peatland can only develop in areas where moisture surplus is positive, i.e., there is more incoming water than evaporation. Although some natural peatlands may have relatively dry appearances, the actual peat deposits are always fully saturated. On the other hand, not all wetlands are peatlands, many wetland types do not accumulate peat. In very humid oceanic climate, peatlands may cover terrain with varying topography (e.g., blanket bogs in north-western Ireland and Scotland) but in most of their distribution, peatlands develop in depressions of the landscape. Indeed, peatlands have their own catchments just like lakes, and the surrounding mineral soil areas supply peatland basins with groundwater and overland flow of snowmelt water, for example. Peat formations develop in intricate interaction with catchment hydrology, reflecting water quality, flow paths and seasonal fluctuations. Climate affects hydrology but also plant productivity, which is the source material for peat. Typically, over 90 % of peat volume consists of water and most peat qualities have high water retention capacity. Peat deposits slow down and redirect water flow in the whole landscape and act as water storages that buffer seasonal discharge, thus, mitigating floods and droughts.



Figure 1. Peatlands are formed in wet depressions in the landscape and make a mosaic with forests and lakes in the boreal Taiga. The Finnish peatland classification has ca. 100 different vegetation types, which exemplifies the importance of these ecosystems to biodiversity. This peatland scenery is from north-boreal zone, Lapland.

One byproduct of the interaction of water, vegetation, and peat is the continuous sequestration of carbon from the atmosphere, as the peat deposit accumulates in thickness and carbon storage. The peatlands of the northern hemisphere, expanding in a circum-polar belt of nemoral to boreal and arctic types, have accumulated ca. 500 Pg carbon (Peta = 10<sup>15</sup>) during the Holocene, an amount roughly equivalent to 60 % of the atmospheric carbon pool. The main cause of the accumulation is the creation of anaerobic conditions in the water-logged peat that greatly hinders decomposition by microbes. Raised bogs are peatlands that have accumulated so thick peat layers that the peatland surface has risen above the reach of groundwater flow. These peatlands are called ombrotrophic (rain nourished) and they often have many meters of peat mainly formed by peat mosses (*Sphagnum*). These mosses have particularly high water-retention capacity, allowing the raised bogs to retain their water storage. Besides raised bogs, peat mosses are also common in poor fens, which are peatlands with groundwater input (i.e., minerotrophic) but where mineral influence is not high enough to buffer against acidity caused by organic acids coming from peat decomposition and from the acidity of the peat mosses. Indeed, raised bogs and poor fens are both characterized by abundance of peat mosses and high acidity, manifested by low pH values (pH 3.5-4.5). The acidity further inhibits decomposition, contributing to the peat formation process. In Finland, acidic bogs and poor fens form a major part of peatlands.

Finland has a high cover of peatlands, and some sources insist that the share of peatlands would be the highest among all countries. Unfortunately, exact comparisons between countries are difficult due to major differences in statistics of land cover categories. The estimate for total peatland cover in Finland is ca. 8.7 million hectares. It is important to note that this figure includes thin-peated moist forests that are only categorized as peatlands in Finnish statistics. Furthermore, it includes degraded peatlands and does not infer area of natural peatland habitats. The lowest figure for Finnish peatlands would be ca. 1.8 million hectares of prevailing habitats, comprising of open (tree cover below 10 %), undrained peatlands with a minimum of 30 cm peat. The gap between these figures does not represent uncertainty, instead, different categorization and the consideration of ecosystem degradation. In every case, Finland has a lot of peatlands and assessing the effects of land use on peatland ecosystems is an immensely important and multifaceted topic. Considering peatland restoration, as potential NBS to mitigate climate change, we first need understanding of processes and data of greenhouse gas (GHG) fluxes from natural and drained peatlands. And before that, a short lesson of main GHG flux components in peatlands.

#### Greenhouse gas fluxes in peatlands - a short lesson

Peat accumulation means a long-term transfer of carbon via photosynthesis and the incompleteness of decomposition to the peat storage, let's call this CO<sub>2</sub> sequestration. Another GHG flux of great significance, especially in peatlands and other wetlands, is the emission of methane (CH<sub>4</sub>). The source of carbon to CH<sub>4</sub> emission is ultimately CO<sub>2</sub> sequestration and many studies have shown that CH<sub>4</sub> is mainly coming from recent additions of labile C-compounds, rather than from the slow decomposition of old organic matter in peat. In short, peatlands sequester CO<sub>2</sub> and produce CH<sub>4</sub> emission to the atmosphere. Since CH<sub>4</sub> is much more potent GHG than CO<sub>2</sub>, a natural peatland can, and often does, have a warming effect if only instantaneous flux is considered. However, CH<sub>4</sub> is unstable in the atmosphere, and it is oxidized to CO<sub>2</sub> at a relatively fast rate. Therefore, the climate effect of peatland GHG fluxes needs to be counted in a timeline of sustained fluxes. With enough time,

the cooling impact from sustained CO<sub>2</sub> sequestration will cancel out the warming impact of CH<sub>4</sub>. This is because the sustained CH<sub>4</sub> flux effect in the atmosphere will level out with time, as the CH<sub>4</sub> is steadily oxidized and turned into CO<sub>2</sub> in atmospheric processes. How much time is required for the cooling effect to emerge depends on the ratio of the CO<sub>2</sub> sequestration and CH<sub>4</sub> emission. If the (molar) ratio is 1, it takes a little over 1,000 years until the GHG flux balance results in a cooling effect (Frolking et al 2006).

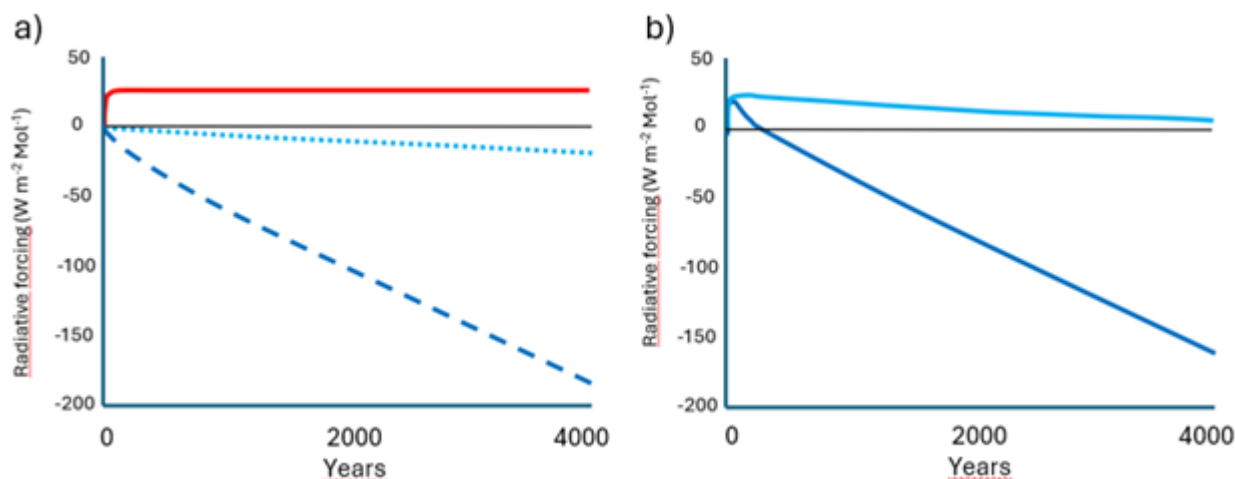


Figure 2. The radiative forcing of constant fluxes of (a) 1 mol yr<sup>-1</sup> CH<sub>4</sub> emission (red solid line), 1 mol yr<sup>-1</sup> CO<sub>2</sub> sequestration (pale blue short dash), and 10 mol yr<sup>-1</sup> CO<sub>2</sub> sequestration (dark blue long dash). The combined effect (b) of 1 mol yr<sup>-1</sup> CH<sub>4</sub> emission and the two alternative CO<sub>2</sub> sequestration rates (pale and dark blues: 1 and 10 mol yr<sup>-1</sup>, respectively) demonstrate the great difference in timing of climate cooling effect (negative forcing) as dependent on balance of CH<sub>4</sub> and CO<sub>2</sub> fluxes (redrawn from Frolking et al 2006).

During the Holocene peatland development, indeed, the climate feedback of each peatland was first warming, but after the early succession phase, a net cooling effect has prevailed over ca. 8000 years until recently, thanks to continued CO<sub>2</sub> sequestration. In another iteration, should a cooling effect be expected within less than 400 years, the CO<sub>2</sub> sequestration needs to be ten times more than CH<sub>4</sub> emission. This poses a serious problem to NBSs with peatlands that is not only physical, but also philosophical and political, truly connecting to the fundamentals of the search for NBSs. While we can acknowledge the immense global scale impact of northern peatlands to the planetary balance with their cooling effect on the climate we experience today, the timelines for the call of NBSs to mitigate current climate crisis are manyfold shorter. Indeed, all instruments planned for climate mitigation have short timespans compared to the millennial history of contemporary peatlands.

#### Peatland degradation by forestry drainage in Finland

Nearly 90 % of original peatland area (in the wide sense) has been degraded by forestry drainage in southern and eastern Finland (Turunen & Valpola 2020). Other land uses have covered smaller area proportions, but they have impacted specific peatland ecosystems and caused specific problems. Agricultural use of peatlands has the longest history, much of which is impossible to trace today, because peatlands have been cleared for fields since prehistoric times. Indeed, one hypothesis for the name 'Finland' relates to the word 'fen', which has many variations in many European languages (fen,

fenn, fin, venn, viana) and it is possible that Finland means the land of fertile fens that could be easily cleared to fields and pastures. In every case, many minerotrophic fens have been cleared for agriculture, the treatments including ditching, fertilizing, and sometimes also burning of surface peat. Today, peatland fields are hotspots of GHG emission in many parts of Europe, including Finland. A specific feature of peatland fields is high emission of N<sub>2</sub>O, a GHG with much higher global warming potential than CO<sub>2</sub> or CH<sub>4</sub>. While restoration of peatland fields is a timely topic, e.g., in northern Germany, there are practically no cases yet in Finland. Another ecosystem degrading use of peatlands is peat mining for energy production and for peat products in horticultural growth media, and other applications. While peat mining has covered only ca. 1.5 % of total peatland area in Finland, it is important to realize that it has focused on thick peated, large peatlands. Among this category, peat mining has already affected a large portion of peatlands, possibly close to 10 %. Notice that peat mining is often called 'peat production', which is counterintuitive because the true producer of peat is the living peatland ecosystem.

Forestry drainage comprises by far the biggest area proportion of land use in Finnish peatlands. Furthermore, its history is relatively recent and uniform across the country. Although some forestry drainage had been practiced already during early 1900s, most of this activity took place during late 1960s to 1990s. Within these few decades, over 5 million hectares of peatlands were drained, to promote tree growth for production of wood for timber and pulp industry. In total, Finland has ca. 1.4 million kilometers of peatland ditches! With such intensity of the drainage campaign, it is no surprise that a proportion of the drained peatland area failed to produce forest growth. Today it is estimated that between 0.5 to 1 million hectares of forestry drainage was unsuccessful. Furthermore, the drainage caused manifold problems to biodiversity and ecosystem services. Concerning climate impacts of peatland use, the case of forestry drainage is much more complex than peat mining for energy, hence, the choice of specific attention on forestry drainage here. Furthermore, restoration has mainly focused on forestry drained peatland areas in Finland and, thus, that's where near future potential of any larger scale impact lies.



Figure 3. Forestry drainage redirects water flow through ditches and lowers water level. In this case, tree growth is weak, but vegetation has changed: lichen and woody shrubs have replaced peat mosses and sedges.

The main treatment in forestry drainage of peatlands is the lowering of water level by digging ditches to convey water away from peatland basin. The ditches are arranged in planned networks that effectively disconnect the peatland from its catchment – any water coming from the catchment rather flows away through the ditch network than spreads over the peatland surfaces. The lowering of water level increases water-table depth and exposes surface peat layers to aerobic oxidation and decomposition, causing increased loss of CO<sub>2</sub>. In the same time, the increasingly aerobic conditions effectively decrease CH<sub>4</sub> emissions. Thus, the climate impact is dependent on the background GHG fluxes before drainage and it is also strongly tied to the timescale of impact assessment. There are many rival estimates of carbon loss due to drainage. With resampling of previously known peat layers, it has been estimated that drainage has caused ca. 150 g C m<sup>-2</sup> yr<sup>-1</sup> loss, on average (Simola et al. 2012). On the other hand, modeling studies on the situation 30-50 years after drainage have indicated that drained peatlands of certain types can act as C sinks, because of high litter input from trees (Ojanen et al. 2013). In the bigger picture, it is well established that drainage tends to cause high carbon loss from organic soils and prompt restoration is suggested as a remedy to stop losses (e.g., Leifeld & Menichetti 2018). Let's delve deeper into the case of forestry-drained peatland restoration, as a potential NBS for climate mitigation, but keep in mind that consensus is missing about the impacts of drainage, the continuation of which makes the important reference scenario of restoration. Furthermore, restoration

is an important NBS in many aspects, including water quality and biodiversity, although focus here is limited to climate mitigation.

### The problem

Forestry drainage of peatlands affects most functions of peatland ecosystems, bringing economical gains when successful, but causing many problems, including weakening of ecosystem services and loss of biodiversity. Considering climate impacts, the main problem is the CO<sub>2</sub> emissions from peat decomposition, stimulated by lowered water level.

### Nature-Based Solutions

Preventing CO<sub>2</sub> emissions and re-establishing CO<sub>2</sub> accumulation in peat by hydrological restoration

The restoration is considered as a true NBS because it is expected to initiate natural secondary succession towards a functional peatland ecosystem (Fig. 4). The aim of restoration, in general, is to re-establish abiotic conditions that facilitate return of target ecosystem structures and functions. The target ecosystem is represented by the original, natural peatland type. However, it is generally recognized that the trajectory for post-restoration development has such a heavy legacy from the degradation that a perfect match with the original state cannot be expected. While this is a reasonable and unavoidable premise, it is worth noting that restoration cannot be left loose without specific goals, else it would be impossible to assess success. In the case of climate impacts, we can set the goal that restoration should improve the situation compared to continued drainage.

### Restoration measures in practice

Restoration of forestry drained peatlands starts with planning. Topographic maps can be used for catchment delineations and old aerial images work well to reveal different vegetation zones, patterns and flow paths of water. Important considerations include landownership and possible effects to neighboring real estates or downstream waters. In general, blocking water flow through ditches is the most important part of the restoration measures. This is done by building dams and filling ditches with peat. The left-over peat dug out during the ditching is put back and often additional peat is dug, leaving small pools in the restored peatland. The placing of dams is planned so that water flow would be directed along the likely original flow paths, zones of the peatland that would then develop into the wettest areas. And in general, the aim is that water would spread over the peatland area and not continue flowing along the ditch lines.

Second main measure in our restoration case is the cutting of trees. This naturally depends on the targeted peatland type. When the target is an open, treeless peatland type, all or most trees are removed. This can seem controversial and, indeed, coupled with heavy excavator work on ditches, outright ugly. However, tree cover does not belong to open peatlands, and it would hamper establishment of species requiring openness. Furthermore, trees have high evapotranspiration rate and they may lower water level, hence, preventing rewetting and post-restoration succession. One interesting fact is that tree harvesting can cover some of the expenses of restoration, making it economically more feasible. Considering unsuccessful forestry drainage, restoration may in fact be

the only way to enable tree harvesting, giving it additional motive, when mere tree cutting would not be profitable.



Figure 4. In a drained peatland (left) forest vegetation dominates and surface peat is decayed into dark brown humus by aerobic heterotrophs. Ten years after restoration (right) the new surface peat is formed by peat mosses on top of the peat stratum (arrow) degraded during the drainage. The new moss material can accumulate carbon with a high rate of ca. 500-800 g CO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>, while decomposition of underlying old peat is slowed down by anaerobes.

#### Assessing success of restoration as NBS for climate change mitigation

Although the increase of CH<sub>4</sub> emission appears to unavoidably cause a warming effect after restoration, the situation is not so simple, and not as dire as it might seem. This is because the estimation of climate impact of restoration needs a reference situation, a control treatment, which is obviously the continuation of the current land use. In our example case, we need to compare restoration to the continuation of forestry drainage. This brings into consideration the effects of tree growth and the increased decomposition due to the drawdown of water level. Drainage exposes old peat layers to aerobic decomposition, causing CO<sub>2</sub> losses, while it simultaneously cuts down CH<sub>4</sub> emissions. Recently, Laine et al (2024) estimated that restoration could only bring climate mitigation impact when directed to nutrient-rich drained peatlands, because they would have big CO<sub>2</sub> emissions unless restored. In contrast, they did not find climate mitigation potential in nutrient-poor drained peatlands, where soil acted as a modest CO<sub>2</sub> sink already in the drained state (ca. -70 g CO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>). This result is highly controversial, however, because different data sources and research methods disagree on drainage impacts and because data was completely missing from restored peatlands and values from natural sites were used as surrogates to restoration. While the case remains unsolved, lacking data from restored sites, it should be ever more interesting and important to explore the potential climate mitigation with alternative scenarios. I made simulations with the REFUGE 4 -model (Lindroos 2023) on impacts of restoration to demonstrate how 10-fold increase of CH<sub>4</sub> emission

causes warming effect relative to drained state. With high enough CO<sub>2</sub> sequestration, a cooling impact is achieved in under 50 years (Fig. 5). The cumulative effect for cooling takes longer, however, due to the initial warming effect. All presented scenarios have GHG fluxes well within ranges to be expected in drained and restored peatlands, but they are not necessarily representative estimates, this is meant for demonstration of possible outcomes.

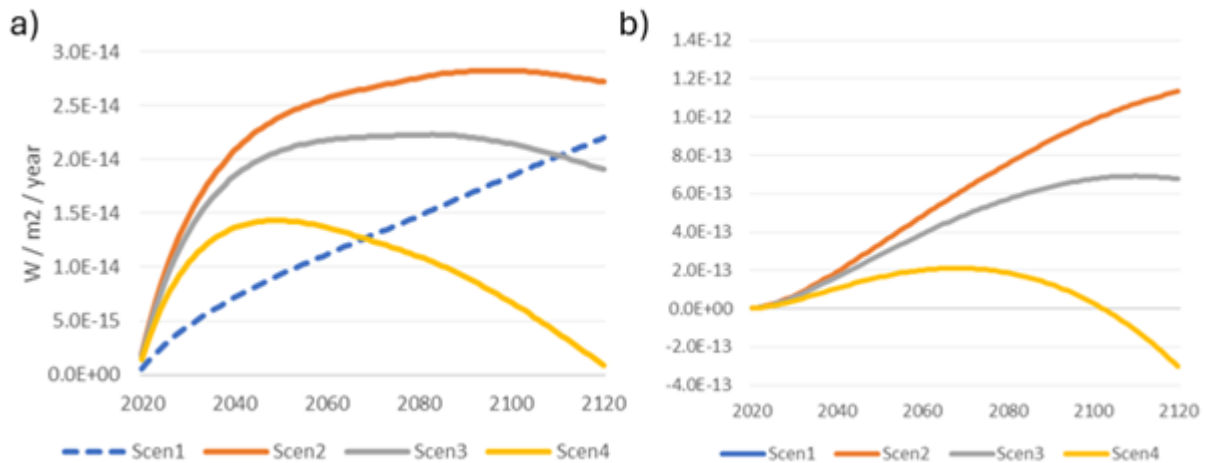


Figure 5. Annual radiative forcing of sustained, constant GHG fluxes (a) in drained (blue dashed line) and restored peatlands (solid lines), and (b) the cumulative forcing of restoration relative to drained reference (positive = warming, negative = cooling). The scenarios have different GHG net fluxes (g m<sup>-2</sup> yr<sup>-1</sup>):

Scen1 = drained, 100 g CO<sub>2</sub> emission, 1 g CH<sub>4</sub> emission, 0.008 g N<sub>2</sub>O emission

Scen2 = restored, 100 g CO<sub>2</sub> sequestration, 10 g CH<sub>4</sub> emission, 0.003 g N<sub>2</sub>O emission

Scen3 = restored, 200 g CO<sub>2</sub> sequestration, 10 g CH<sub>4</sub> emission, 0.003 g N<sub>2</sub>O emission

Scen4 = restored, 400 g CO<sub>2</sub> sequestration, 10 g CH<sub>4</sub> emission, 0.003 g N<sub>2</sub>O emission

Exercise!

You can make your own simulations with the same model introduced in this text, with an easy-to-use Excel notebook. Please proceed to the next page for the instructions.

References

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