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Global peatland greenhouse gas dynamics: state of the art, processes, and perspectives

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Summary

Natural peatlands regulate greenhouse gas (GHG) fluxes through a permanently high groundwater table, causing carbon dioxide (CO_2) assimilation but methane (CH_4) emissions due to anaerobic conditions. By contrast, drained and disturbed peatlands are hotspots for CO_2 and nitrous oxide (N_2O) emissions, while CH_4 release is low but high from drainage ditches. Generally, in low-latitude (tropical and subtropical) peatlands, emissions of all GHGs are higher than in high-latitude (temperate, boreal, and Arctic) peatlands. Their inherent dependence on the water regime makes peatlands highly vulnerable to both direct and indirect anthropogenic impacts, including climate change-induced drying, which is creating anthro-natural ecosystems. This paper presents state-of-the-art knowledge on peatland GHG fluxes and their key regulating processes, highlighting approaches to study spatio-temporal dynamics, integrated methods, direct and indirect human impacts, and peatlands' perspectives.

I. Introduction

Peatlands cover only *c.* 3% of Earth's land but store up to one-third (600–650 petagrams; Pg) of the terrestrial organic carbon (C; Dargie *et al.*, 2017) and up to 10% of the global terrestrial nitrogen (N; Leifeld & Menichetti, 2018). Most peatlands are in boreal and arctic zones, while *c.* 14% are in (sub)tropical regions, primarily as peatland forests. Although peatlands hold the largest terrestrial pool of organic C and have a cooling effect by sequestering carbon dioxide (CO_2), in the short term, they are generally weak C sequesters due to slow peat growth and the fact that C accumulation takes thousands of years. However, over 1000 years, no other terrestrial habitat sequesters C so strongly. Increasing human influence over the last three centuries has caused extensive peatland loss globally (Fluet-Chouinard *et al.*, 2023). This paper provides an overview of the state of the art in peatlands' greenhouse gas (GHG) fluxes and the key processes regulating them, along with novel integrated methods for measuring these emissions. It also presents perspectives on peatlands development based on trends in changing environmental conditions and GHG emissions.

II. State of the art

1. Natural and managed peatlands

Undisturbed (natural) boreal/arctic, temperate and tropical peatlands function as C sinks (*c.* 10–1000 kg CO_2-C ha^{-1} yr^{-1}), moderate sources of methane (CH_4) (10–500 kg CH_4-C ha^{-1} yr^{-1}), and very weak sources of nitrous oxide (N_2O) (< 1.0 kg N_2O-N ha^{-1} yr^{-1}) (Fig. 1; Supporting Information Table S1). Northern boreal peatlands, distant from anthropogenic pressures, store the majority of the global peatland C stock, while tropical peatlands, which contain up to 16% of peatland C (105 Pg; Dargie *et al.*, 2017), are often near large and rapidly growing human settlements (Page *et al.*, 2022). Most tropical peatlands are peat swamp forests, and their CO_2, CH_4, and N_2O emissions vary with wet and dry seasons; however, global warming has disrupted this seasonal pattern, leading to more erratic cycles (Page *et al.*, 2022). In natural peatlands, N_2O flux is negligible, varying between low emission and very low sequestration (Pärn *et al.*, 2018), while CH_4 is emitted under anaerobic conditions. Draining peat accelerates decomposition, releasing significant amounts of CO_2. Additionally, N_2O emissions can be high due to high N content in peat, but CH_4 emissions are reduced. Consequently, peatlands drained for forestry, agriculture, and other purposes have shifted from long-term C sinks to sources of CO_2 and N_2O emissions, contributing *c.* 5% of global anthropogenic GHG emissions (Joosten *et al.*, 2016) and *c.* 70% of all organic soil N_2O emissions (Pärn *et al.*, 2018).

Global warming exerts direct or indirect pressure on nearly all natural terrestrial ecosystems, potentially increasing GHG emissions. Because of their inherent dependence on the water regime, peatlands are among the most vulnerable areas directly or indirectly influenced by human activities, whereby they can be classified as anthro-natural ecosystems. This term refers to 'undisturbed' peatlands affected by low or indirect anthropogenic influences from global warming. The effect of global warming (anthro-natural effect) is most clearly manifested spatially in the form of locations with higher emissions (hot spots) and temporally in the form of extreme events (hot moments). Distinguishing the anthro-natural terrestrial ecosystem type is essential, as significant uncertainties in natural GHG budgets are often overlooked in models and IPCC reports. GHG fluxes between the atmosphere and natural terrestrial ecosystems can be significantly greater than those from fossil fuel combustion, meaning that even small uncertainties in these estimations can skew total GHG budgets (IPCC, 2021). Thus, anthro-natural ecosystems warrant more attention alongside natural and anthropogenic systems.

2. Hot spots and hot moments, ecosystem complexity

In peatlands, GHG dynamics at both local and large scales, the hot spots and hot moments play an important role. Temperature and water regime are leading factors of this regulation. A fluctuating water regime creates hot spots and hot moments for N_2O emissions (Mander *et al.*, 2021) and inundated conditions for CH_4 emissions (Evans *et al.*, 2021). The impact of global warming on GHG emissions from northern peatlands is not well known. Recent studies from northern Sweden show that, over the 45-year period, warming caused changes in vegetation cover, shifting the net radiative forcing of peatlands from negative to positive (Varner *et al.*, 2022). However, the change in CH_4 and CO_2 balance has not been large, and some areas still remain a net sink of C, with CH_4 emission offsetting only 2–17% of the CO_2 uptake rate (Holmes *et al.*, 2022). Other studies from boreal and Arctic peatlands demonstrate that permafrost thawing may release significant amounts of C from peat soils (Jones *et al.*, 2017), and this release may increase sharply in the coming decades (Turetsky *et al.*, 2020). Emissions are increasing, particularly during the nongrowing season (Natali *et al.*, 2019; Rafat *et al.*, 2021), with over 70% of annual N_2O emissions occurring during the cold period in drained peatland forests (Viru *et al.*, 2020). In tundra peatlands, high N_2O emissions have been observed from elevated plateaus without vegetation and palsas (Marushchak *et al.*, 2011).

Warmer temperatures alter wildfire regimes, with droughts increasing the risk of burning in peatlands (Byrne *et al.*, 2024). Frequent fires can transform peatlands from net sinks to net sources of C and GHGs. Drained peatlands are particularly vulnerable to wildfires, resulting in substantial GHG emissions (Page *et al.*, 2022). Although tropical undisturbed peatlands are found to be global hotspots for N_2O emissions (Tian *et al.*, 2020), emissions can vary significantly from high levels in peatlands with elevated N content and neutral pH (Pärn *et al.*, 2023) to low emissions in those with low N content and low pH (Pärn *et al.*, 2018).

Forested peatlands are more complex ecosystems than open ones (Fig. 2), as tree and palm stems can release substantial amounts of CH_4, especially during wet periods (Pangala *et al.*, 2017; Mander *et al.*, 2022; Ranniku *et al.*, 2024). Additionally, large N_2O fluxes from the soil may be absorbed by the canopy, although the mechanisms remain largely unknown (Mander *et al.*, 2021). The dynamics of CH_4 in peatland forest canopies are also unclear, as the canopy can both oxidize and produce CH_4 (Jeffrey *et al.*, 2021; Gauci *et al.*, 2024).

III. Processes

1. Carbon

Constant water saturation of peat reduces oxidation, allowing C to accumulate. CO_2 assimilation by slow-growing peat-forming plants is low, whereas CH_4 emissions can be high due to anaerobic conditions and intensive methanogenesis. CO_2 flux negatively correlates with groundwater level (GWL) and soil water content (SWC), while CH_4 flux shows a positive relationship with GWL. Oxygen levels in soil and water regulate the CO_2/CH_4 balance, for example, with wet depressions and lawns emitting CH_4 and hummocks oxidizing it in boreal bogs (Korrensalo *et al.*, 2018). Drainage causes organic C to be mineralized and lost as gaseous fluxes (CO_2 and/or CH_4), and laterally as particulate organic carbon (POC) and dissolved organic carbon (DOC). Soil organic matter recalcitrance (see Box 1) is crucial in C dynamics. Hodgkins *et al.* (2018) found that near-surface peat in boreal regions has more carbohydrates and fewer aromatic compounds

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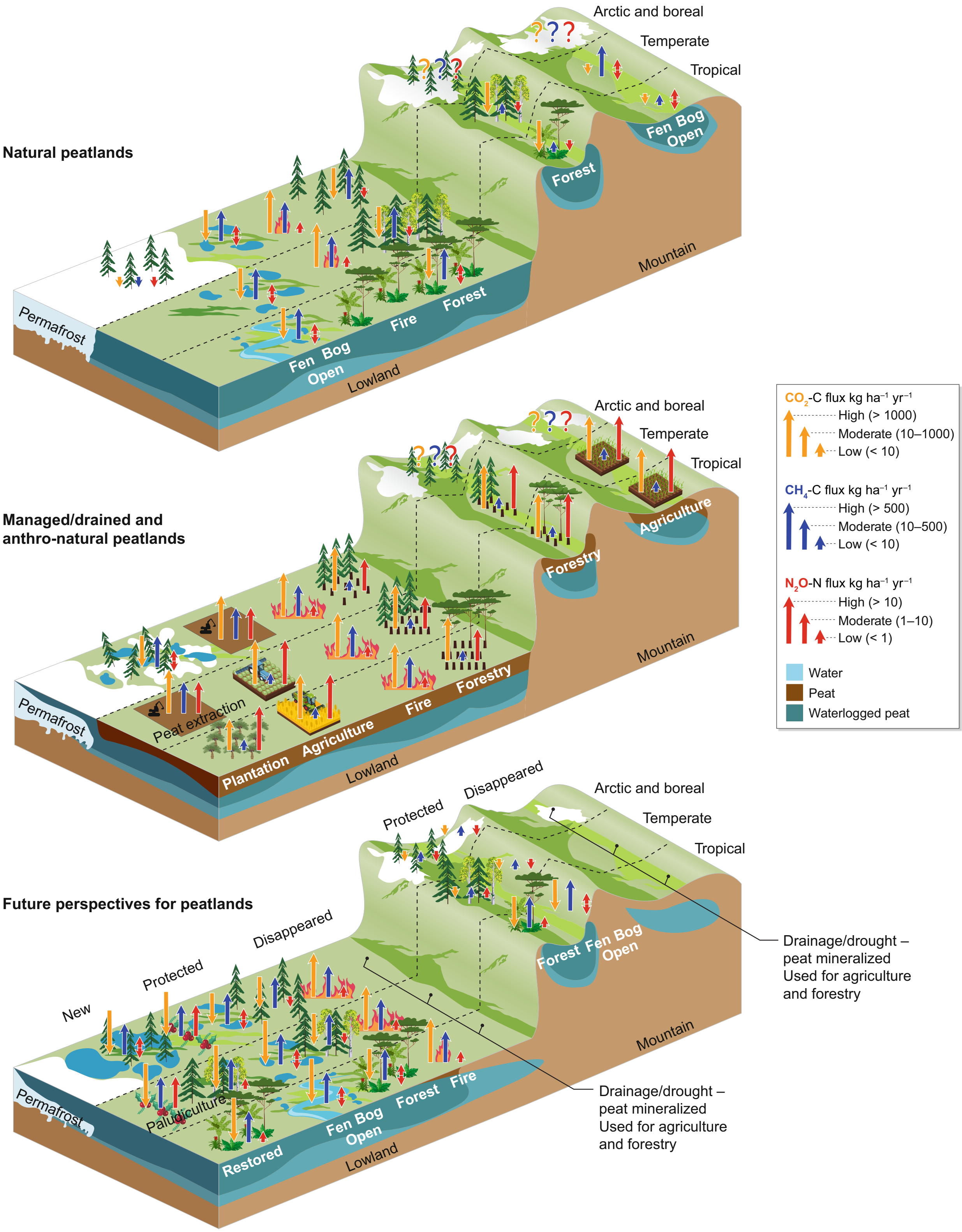

Fig. 1 Global peatland greenhouse gas emissions from natural, managed/drained, and anthro-natural peatlands, along with future perspectives. Flux values are based on review and generalization papers: Frolking *et al*. (2011), Turetsky *et al*. (2014), Abdalla *et al*. (2016), Wilson *et al*. (2016), Pärn *et al*. (2018), Page *et al*. (2022), Jauhiainen *et al*. (2023), Mander *et al*. (2024). Estimated global warming potential values (CO_2-$C_{equivalent}$ ha^{-1} yr^{-1}) are shown in Supporting Information Table S1. CH_4, methane; CO_2, carbon dioxide; N_2O, nitrous oxide.

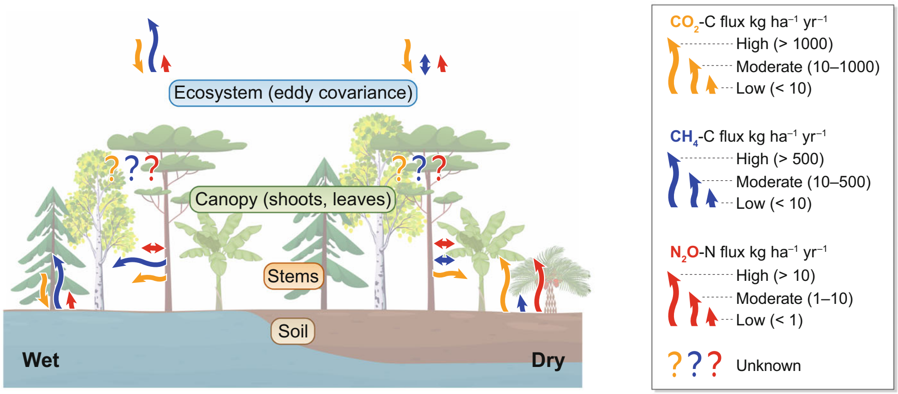

Fig. 2 Estimated greenhouse gas emissions from different forest compartments during wet and dry periods. Flux data are based mainly on: Pangala *et al*. (2017), Tang *et al*. (2018), Wong *et al*. (2018), Griffis *et al*. (2020), Sjøgersten *et al*. (2020), Mander *et al*. (2021, 2022, 2024), Soosaar *et al*. (2022), Jauhiainen *et al*. (2023), Pärn *et al*. (2023), Gauci *et al*. (2024), Machačova *et al*. (2024). CH_4, methane; CO_2, carbon dioxide; N_2O, nitrous oxide.

Box 1. Main processes and methods for studying peatland greenhouse gases

Two antagonistic processes – production and consumption – drive GHG fluxes in peatland ecosystems. CO_2 flux is determined by the balance between C assimilation during photosynthesis (CO_2 consumption) and respiration from vegetation (autotrophic) and soil (plant root-mediated autotrophic and microbial heterotrophic) (CO_2 production). CH_4 is produced through anaerobic archaeal methanogenesis (controlled by *mcrA* genes) and consumed primarily via aerobic bacterial methanotrophy (controlled by *pmoA* and *mmoX* genes). As soil water content regulates oxygen levels in soil pores, high groundwater levels and inundation mainly regulate CH_4 fluxes. Peat decomposing intensity largely depends on C recalcitrance, the ratio of carbohydrates and aromatic compounds, with easily degradable C compounds (e.g. carbohydrates) lost first, while more complex aromatic compounds are more resistant, that is more recalcitrant. While CO_2 and CH_4 fluxes and emission peaks (hot moments) show a relatively clear seasonal rhythm (warm vs cold and/or wet vs dry period), N_2O emission hot moments occur irregularly, primarily depending on rapid soil moisture changes and the soil freeze–thaw pattern in boreal and temperate zones.

The key microbial taxa and functions driving N_2O emissions remain unclear due to the complexity of the N cycle. Denitrification is a multi-step process where nitrate (NO_3^-) is reduced to N_2O or N_2, common in oxygen-depleted environments. Soils rich in *nirK*, *nirS*, and *nosZ* genes suggest high N_2O production, though 30–80% may convert to N_2 before release. Fungal denitrifiers, though relatively understudied, significantly contribute to N_2O production in tropical and temperate wetland forest soils. The key genes, like fungal *nirK* and *p450nor*, have enhanced our understanding of fungal denitrification in soils. The *amoA* gene controlling bacterial and archaeal ammonia oxidization plays a central role in nitrification and N_2O emissions. Recent discoveries suggest that the abundance of nitrifying archaea is a key factor explaining N_2O emissions from wetland soils globally. However, hybrid N_2O formation, which involves ammonia oxidation, can be a major process of N_2O production in drained peatland forests. Furthermore, comammox bacteria are considered as 'green' nitrifiers for producing less N_2O, yet their diversity patterns in many ecosystems, including peatland forests, remain largely unknown.

State-of-the-art and novel methods for measuring CO_2, CH_4, and N_2O fluxes in peatlands primarily use eddy covariance, chamber, and gas-chromatograph methods, integrated with isotope analysis, and microbiome characterization related to the C and N cycle (Table 1).

than (sub)tropical peatlands, where peat persists better despite warmer temperatures. Climate-induced droughts increase the loss of easily degradable C compounds via gaseous and lateral pathways, with POC and DOC losses accounting for up to half of total C stock changes (Rosset *et al.*, 2022). Soil organic matter decomposability is an important indicator for modelling CO_2 and CH_4 fluxes (Hu *et al.*, 2024).

Peatlands are a significant global source of CH_4, contributing *c.* 10% of total terrestrial CH_4 emissions; however, due to peat degradation, their share is decreasing (Saunois *et al.*, 2024). Although CH_4 has a much shorter lifetime than CO_2, its emissions eventually reach equilibrium, making CO_2 uptake more important over a 100–300-year timescale. As a result, historically, most peatlands acted as net coolers of the atmosphere (Mitsch *et al.*, 2013). However, in a warming climate, the range of C losses from boreal peatlands can be up to 18 times faster than historical rates of accumulation, with substantial emissions of CO_2 and CH_4 to the atmosphere (Hanson *et al.*, 2020). CH_4 is emitted through diffusive flux from peat soil, ebullition under inundated conditions, drainage ditches, and via aerenchymous plants (Ge *et al.*, 2024), where the latter also increase CH_4 production by providing C to methanogens (Espenberg *et al.*, 2024). Forest stems and canopies influence CO_2 and CH_4 exchange by absorbing and releasing C (Gauci *et al.*, 2024). Biogenic volatile organic compounds (BVOCs), such as terpenes, emitted by peatland plants affect atmospheric chemistry (Junninen *et al.*, 2022), contributing to global warming by influencing secondary organic aerosols and ozone formation (McGenity *et al.*, 2018).

2. Nitrogen

N in peatlands plays an important role in N_2O dynamics, and is influenced by the balance between nitrification, denitrification, dissimilatory nitrate reduction to ammonium (DNRA), and other processes, leading to N imbalances and losses, particularly in drained or disturbed conditions (Butterbach-Bahl *et al.*, 2013). Unlike the unidirectional relationship between SWC and CO_2 or CH_4 (Evans *et al.*, 2021), N_2O emissions follow a unimodal (bell-shaped) relationship, peaking at 40–70% SWC (Pärn *et al.*, 2018; Mander *et al.*, 2021). Therefore, both extreme conditions – too dry and too wet – are not conducive for N_2O emission, while the mid-range conditions with optimal O_2 and moisture levels allow both dominating processes, denitrification and nitrification, to combine and contribute to N_2O production (Bahram *et al.*, 2022; Kazmi

Table 1 Key topics and research perspectives related to the greenhouse gas (GHG) emissions in peatlands and forests on organic soils.

Key topics and research perspectives	Importance	References
Spatial and temporal dynamics of GHG fluxes		
Hot spots (tropics, drainage for agricultural use and forestry, peat mining)	Key factor for global GHG modelling, including peatlands, insufficiently understood	Pärn *et al*. (2018); Tian *et al*. (2020)
Hot moments (N_2O: freeze–thaw cycles, shoulder of SWC and GWL; CH_4: high GWL, both soil and tree stems, wet periods in tropics)	Key factor for ecosystem-level and global GHG modelling, including peatlands, insufficiently understood	Mander *et al*. (2021, 2022); Wang *et al*. (2023); Kazmi *et al*. (2023)
Droughts and wildfires	Leading factors of peat losses and peatland disappearance	Zeng *et al*. (2023); Byrne *et al*. (2024)
Methods		
High-resolution mass spectrometry (HRMS) and reactomics	Novel method for determination of peat recalcitrance – the ratio of carbohydrate and aromatic compounds in peat	Wang *et al*. (2021); Verbeke *et al*. (2022)
Integrated soil and stem flux chambers, and eddy covariance analysis of all GHGs	Key factor in GHG flux modelling	Mander *et al*. (2021, 2022); Ranniku *et al*. (2024)
Integrated microbiome and isotope analysis	Key issue in partitioning processes which control CH_4 and N_2O emissions in peatlands	Gallarotti *et al*. (2021); Masta *et al*. (2024)
Modelling of C and N budget dynamics in peatlands	Important tool for the prediction of peatlands' development. Few models for forested peatlands' C budget, and none for N budget	Chadburn *et al*. (2022)
Processes		
Impact of C recalcitrance on long-term CO_2 and CH_4 emissions and lateral losses of C from peat	Key factor in long-term peat losses in drained peatlands, but little understood	Hodgkins *et al*. (2018); Hu *et al*. (2024)
The role of aerenchymous plants and root exudates on CH_4 and N_2O emissions from peat	Significant role in the total CH_4 budget in boreal peatlands, the broader impact combined with root exudates is largely unknown; impact on N_2O less studied	Korrensalo *et al*. (2018); Ge *et al*. (2024); Espenberg *et al*. (2024)
Phyllosphere impact on CH_4 and N_2O balances in peatland forests	Addresses the gap in understanding the physical–chemical and microbiological processes influencing CH_4 and N_2O balances in forest canopies	Sjøgersten *et al*. (2020); Jeffrey *et al*. (2021); Gauci *et al*. (2024); Guerreri *et al*. (2024)
Methanogenesis vs methanotrophy	Improved understanding of the processes regulating CH_4 balances, underpin strategies to reduce CH_4 emissions as well as fluvial C losses	Gios *et al*. (2024); Espenberg *et al*. (2024)
Denitrification vs nitrification vs DNRA	Improved understanding of the processes regulating N_2O balances, underpin strategies to reduce gaseous emissions as well as fluvial N losses	Bösch *et al*. (2023); Espenberg *et al*. (2024); Masta *et al*. (2024)
Impact of BVOCs on GHG fluxes in peatlands	Largely unknown, initial studies indicate impact on CH_4 fluxes	Junninen *et al*. (2022)
Integrated impact of soil moisture changes and microbiome dynamics on GHG fluxes in peatlands	Microbiome dynamics is a potential indicator for modelling of peatlands C and N	Bahram *et al*. (2022)
Impact of peat microbiome diversity and mycorrhiza on GHG fluxes in peatlands	Largely unknown, the impact on GHG fluxes yet to be fully analyzed	Storer *et al*. (2018); Wang *et al*. (2021); Page *et al*. (2022)
Direct and causal human impact, future perspectives		
Anthro-natural (peatlands where GHG balance is altered due to global warming), disturbed, and managed peatlands	Peatlands and organic soils – most vulnerable terrestrial ecosystems, suffering from droughts (e.g. anthro-natural ecosystems)	Hugelius *et al*. (2014)
Disappearing natural peatlands	Most vulnerable peatland ecosystems in tropics and mountains	Page *et al*. (2022)
Restoration pathways	Variety of pathways (long-term restoration, paludiculture, shallow lakes, wet forests, and wet grasslands) exist, but rewetting is essential to preserve peat	Page *et al*. (2022); Mander *et al*. (2024)
Formation of new peatlands	Occurs through permafrost thawing and changes in water availability at the warm and cool climatic margins in the Arctic and northern regions	Hugelius *et al*. (2014); Turetsky *et al*. (2020)

BVOC, biogenic volatile organic compound; C, carbon; CH_4, methane; CO_2, carbon dioxide; DNRA, dissimilatory nitrate reduction to ammonium; GWL, groundwater level; N, nitrogen; N_2O, nitrous oxide; SWC, soil water content.

et al., 2023). In very wet conditions, the denitrification process ends with N_2 production, while in very dry conditions, N cycle processes become inactive. Fluctuations in the water table causing changes in soil moisture and consequent effects on N_2O producing and reducing microbes is the main mechanism for N_2O release from peat.

N-cycle microbiome in peatland soils has been better studied in temperate and boreal zones (Truu *et al.*, 2020; Wang *et al.*, 2021; Masta *et al.*, 2024), while less is known about tropical peatlands (Espenberg *et al.*, 2018; Bahram *et al.*, 2022). Additionally, integrated ^{15}N isotopologue and N-cycle microbiome studies have proven to be effective tools for studying the N cycle (Gallarotti *et al.*, 2021; Gios *et al.*, 2024; Masta *et al.*, 2024).

The N cycle is more complex in the peatland forests due to tree cover (Mander *et al.*, 2021). Research on the phyllosphere's contribution and its microbiome to microbial N cycle processes and N_2O fluxes in peatlands is just beginning (Guerreri *et al.*, 2024; Machačova *et al.*, 2024). The role of mycorrhizal fungi in N_2O fluxes has received little attention, although arbuscular mycorrhizal fungi (AMF) can reduce N_2O emissions in agricultural soils and other hotspots (Storer *et al.*, 2018). Additionally, interactions among different fungal groups, such as saprotrophic, ericoid, and ectomycorrhizal fungi, significantly influence organic matter accumulation and N recycling (Fanin *et al.*, 2022). Understanding the sources and sinks of N_2O in peatland forests and the interplay among microbial groups affecting N cycle processes is crucial for predicting future climate developments. While modelling of peatlands' ecohydrological regimes and GHG exchange is common, a few models exist for peatland forests' C and N budgets (SUSI, Forest-DNDC, JULES), and no N_2O budget models are known.

IV. Perspectives for peatland development and research needs

1. Degradation and formation of new peatlands

Drainage for forestry, agriculture, and peat mining is the main cause of peatland degradation in southern boreal and temperate peatlands. Some countries have established restrictions to minimize intensive peatland management. Most tropical peatlands are forest swamps, and the loss of forest cover increases peat oxidation, the risk of fire and flooding, and the resource loss for local communities. However, the higher recalcitrant organic C in tropical peat may enhance resilience to disturbances.

Peatlands drainage for agriculture and forestry, along with climate warming-induced droughts, is expected to increase CO_2 emissions by 1.13 $PgCO_2$-eq yr^{-1}, while CH_4 emissions may decrease by only 0.26 $PgCO_2$-eq yr^{-1}. This results in a net increase in C-bound GHGs of 0.73 to 0.86 $PgCO_2$-eq yr^{-1} over the next 75 years, according to different IPCC's Representative Concentration Pathways (Huang *et al.*, 2021; IPCC, 2021). With droughts likely to become more frequent, peatland ecosystems will experience gross primary production (GPP) losses that outpace CO_2 fertilization-related GPP increase, particularly impacting croplands on peat soils (Zeng *et al.*, 2023). Additionally, mountain peatlands are likely to face extreme climatic events in the future. Severe droughts may shorten the growing season due to significant water stress, disrupting the balance between GPP and ecosystem respiration.

In Arctic and boreal peatlands, permafrost thawing will accelerate, reaching the abrupt thaw phase in up to 20% of the permafrost zone (Turetsky *et al.*, 2020). Ground collapse, rapid erosion, and landslides may impact 50% of permafrost C; however, the contribution of peatlands to this process is uncertain. Shallow lakes and new wetlands formed by thawing will emit significant amounts of CH_4, although vegetation may partially offset C release. These new shallow water bodies could support the growth of peat-forming mosses and vascular plants, potentially evolving into new peatlands (Hugelius *et al.*, 2014).

2. Protected and restored peatlands

Protection is an effective strategy for maintaining peatlands, particularly in the areas with favorable hydroclimatic conditions, such as alluvial peatlands, forest peat swamp domes, and less disturbed permafrost tundra, which are less vulnerable to drought.

Restoration combined with rewetting is an essential measure to halt peat degradation (Mander *et al.*, 2024). Urgent action is needed to restore damaged peatlands, particularly abandoned peat mining areas. Rewetting can transform degraded peatlands into mires, wet forests, shallow waterbodies, and paludicultural land. Although CH_4 emissions may rise in rewetted peatlands, in the long-term perspective, they still mitigate climate warming (Hemes *et al.*, 2018; Günther *et al.*, 2020). Various crops, such as bioenergy crops (e.g. reed, cattails, silver grass, and reed canary grass), wild berries, and *Sphagnum*, are used in paludiculture (Mander *et al.*, 2024); further, methods for cultivating inundation-tolerating palms are becoming increasingly important for tropical peatlands (Page *et al.*, 2022). While afforestation of continuously drained peatlands may enhance economic benefits, it also results in peat loss (Mander *et al.*, 2024). Rewetting and restoring peatlands reduce soil C losses and GHG emissions (Wilson *et al.*, 2016) while decreasing wildfire susceptibility and consequent C losses. Without restoration or controlled exploitation, drained peatlands are projected to emit 1.91 Pg CO_2-equivalents annually, undermining efforts to limit global warming to below +1.5 to +2°C (Leifeld & Menichetti, 2018). Thus, improved management of peatlands is essential for climate change mitigation.

V. Conclusions

The rising pressures from human activities, along with increasing global air temperatures, shifting ecohydrological patterns, and more frequent severe droughts, will significantly alter C and GHG exchange rates in peatlands, reducing their ability to act as net coolers of the atmosphere. Without urgent action, peatlands may disappear within the next 100–150 years in critical regions. Preserving pristine wetlands, restoring and rewetting drained peatlands, and developing paludiculture are essential strategies to save peatlands, and these efforts must be intensified. The enhanced CH_4 emission in restored peatlands is outweighed by the climate benefit of halting the large CO_2 emissions from drained peatlands. Because of the high CH_4 emission, the radiative balance of the restored peatlands may be a net warming. In peatlands, the time factor must be considered not against the null state but against the long-term net warming effect of drained peatlands, which is avoided by the restoration.

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Competing interests

None declared.

Author contributions

ÜM and ME developed the concept. ÜM, ME and MÖ contributed to writing.

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Supporting Information

Additional Supporting Information may be found online in the Supporting Information section at the end of the article.

Table S1 Estimated greenhouse gas flux budgets from natural, damaged, and perspective peatlands.