Wetlands and Methane

Technical paper

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Wetlands and moorland on the national park Groote Zand, Drenthe, The Netherlands. By Sander Meertins

Foreword

Wetlands International acknowledges the importance of acting on methane to reduce the potential of global warming. The anaerobic soil conditions that are an inherent feature of wetlands enable the highly effective long-term sequestration and storage of soil carbon, but can also lead to the release of methane, as part of their natural function. Through the restoration of wetlands, there may be a transient warming effect of methane emissions before they return to their natural function and no longer contribute to anthropogenically induced global warming. In the long term, the capacity of wetlands to sequester and store carbon has a strong net cooling effect on the atmosphere. To reduce global greenhouse gas emissions, conservation and restoration of wetlands play a key role.

This report outlines the contribution of wetlands to global methane output; differences between natural versus anthropogenic methane emissions; wetlands management and restoration in the context of the ecosystem services they provide for the benefit of nature, climate, and people.

Capybara, family with young, Pantanal, Brazil.
Adobe Stock

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Executive Summary

Methane is a Greenhouse gas (GHG) that is naturally created during anaerobic breakdown by methanogenic microorganisms of organic material, such as leaves and stems or soil organic matter in wetlands. Main sources of anthropogenic methane emissions include fossil fuel production, agriculture (i.a. ruminant livestock), waste, and to some extent burning of biomass and biofuel under low oxygen conditions. Methane emissions from degraded and natural wetlands combined are the largest source (Jackson et al. 2020).

As a greenhouse gas, methane is 27 to 30 times more powerful than carbon dioxide over a 100 year timeframe but is short-lived in the atmosphere (approximately 10 years for CH_4 versus hundreds of years for CO_2). Atmospheric concentrations of methane are rapidly increasing due to human activities.

Methane is naturally produced in wetlands. Prior to the onset of human influence, methane emissions from wetlands formed part of a natural cycle, in which both atmospheric methane concentrations and the climate were stable. Methane emissions from pristine wetlands, or from restored wetlands in which emissions have returned to natural levels, make no contribution to anthropogenically induced global warming.

Methane emissions from wetlands are related to the rate of methane production within the soil, and how much of this methane is consumed before reaching the atmosphere. The pathway from methane production to the atmosphere is critical, as for example where the peatland surface is covered in peat-forming Sphagnum moss, methane emissions may be reduced. However, in damaged wetlands this conversion happens much less, resulting in potentially higher emissions of methane to the atmosphere and associated higher climate warming potential. Drainage can reduce methane emissions from wetlands, but these emissions may be replaced by emissions from ditch networks and enhanced by nutrient or organic matter pollution. Human-made wetlands such as rice paddies and shallow reservoirs can act as new sources of methane emission, often with little or no offsetting CO_2 sequestration.

The strong powerful warming potential, rapidly increasing concentrations and short-lived atmospheric lifetime make action on methane important as part of the Climate-Mitigation Action package and it therefore has attracted significant attention at UNFCCC Conferences of the Parties (COPs). This led to the launch of the Global Methane Pledge during COP26 in Glasgow (2021).

Using best practice in wetland restoration will reduce risks of methane release and will establish the fastest net negative global warming impact. For example, early establishment of sphagnum and other moss carpets on wetlands can act as 'methane filters' reducing methane emissions, whilst open water in direct contact with methane rich soil layers and some plant species can act as vents, bypassing natural methane removal processes.

Wetland restoration is a powerful solution to climate change; a potential short lived methane spike that is sometimes encountered, particularly in nutrient-rich wetlands, is quickly offset by the reduced CO_2 emissions from the no-longer degraded wetlands, resulting in significantly reduced Global Warming impact over decadal time scales.

Why this document?

An important outcome of the 2021 COP26 meeting in Glasgow was the Global Methane Pledge, a commitment by over 100 countries to deliver a 30% reduction in their methane emissions by 2030 (UNFCCC, 2021). It is important to ensure that the Global Methane Pledge aligns with ongoing efforts to protect and restore the world's wetlands, which are globally important carbon stores but can act as natural sources of methane to the atmosphere (Wetlands International, 2021).

In this report, we discuss the contribution wetlands make to the global output of methane; the extent to which these emissions are natural versus anthropogenic, their role in relation to climate change; and the extent to which it may or may not be appropriate to manage wetlands to reduce methane emissions in the context of their wider role as carbon stores, pollutant sinks, havens for biodiversity, and water sources.

Sphagnum moss from the Hiddeser Bent, North Rhine Westphalia, Germany. AdobeStock

Methane in the atmosphere

Methane (CH_4) is the most abundant hydrocarbon in the atmosphere. It strongly absorbs infrared radiation at a wavelength of around 7.7 μm, making it a powerful greenhouse gas. It is well mixed in the atmosphere but relatively reactive, thus playing an important role in regulating both the chemistry and radiative balance of the Earth's atmosphere. Atmospheric methane concentrations have increased from a pre-industrial level of around 720 parts per billion (ppb) in 1750, to almost 1900 ppb in 2021 (NOAA, 2022). During the last decade, the rate of increase in atmospheric methane concentrations has been accelerating, with a record increase of 17 ppb recorded in 2021. Atmospheric methane has a short atmospheric lifetime of around a decade, which means that (compared to CO_2, which has an atmospheric lifetime of over a century) its concentration responds relatively rapidly to changes in annual emissions. This presents both a problem and an opportunity; recent rapid growth in atmospheric methane concentrations, if maintained at current rates, could jeopardise the world's ability to meet Paris Agreement targets aimed at avoiding dangerous climate change (Nisbet et al., 2019). On the other hand, the short lifetime of methane means that measures which reduce methane emissions could achieve rapid reductions in atmospheric concentrations, offering an opportunity to mitigate human impacts on the climate system over short (decadal) timescales.

The climate change impact of methane

The latest IPCC report (AR6) estimates that global temperatures were around 1 °C higher between 2010 and 2019 relative to an 1850-1900 baseline, because of anthropogenic emissions of greenhouse gases (GHGs). It has been estimated that methane has contributed around 0.5 °C of warming, versus around 0.76 °C warming from CO2, and 0.24 °C from all other GHGs combined. The reason that these impacts sum to > 1 °C is that other gases emitted to the atmosphere through human activity, such as sulphur dioxide and nitrogen oxides, have had a counterbalancing cooling effect. Overall, methane is therefore the second most important cause of atmospheric warming.

Quantifying the warming impact of methane compared to other greenhouse gases on a mass balance is challenging. Global Warming Potentials (GWPs) are a widely used concept used to describe the amount of energy absorbed by any GHG, relative to that absorbed by the same mass of CO_2. A higher GWP therefore indicates a more powerful GHG. Given that different GHGs have different atmospheric lifetimes, the GWP for any given gas also varies depending on the timescale over which its warming impact is being assessed. In the case of methane, which is a more powerful GHG than CO_2, but with a shorter atmospheric lifetime, its GWP decreases for longer

Panoramic landscape scenery of marsh wetland full of grass with heron looking for fish during sunset at Thalaynoi, Phatthalung, Thailand. AdobeStock time horizons. The most recent IPCC report (IPCC, 2021) assigns GWP values for biologically produced methane (for example that derived from wetlands) of 80.8 on a 20-year timeframe, and 27.2 on a 100 year timeframe. Over a 500-year time horizon, the GWP of methane declines to around 8. Although the 100-year GWP value (GWP100) is widely used, there has been much debate as to whether this is the most appropriate way to consider methane's contribution to Earth's radiative balance. In general, GWP100 will tend to over-estimate the long-term warming effect, while dramatically underestimating the near-term impact of any new methane source, or step change increase in an existing source (Lynch et al., 2020). In effect, the GWP concept works well for gases that remain in the atmosphere for long periods of time, and therefore effectively accumulate in response to human emissions. For short-lived gases such as methane, on the other hand, atmospheric concentrations rapidly approach a steady state, which is determined by the balance of emissions and removal processes. Crudely, therefore, the warming impact of CO_2 can be considered to depend on the total amount of CO_2 emitted to the atmosphere through human activity, whereas the warming impact of methane depends primarily on the present-day rate of emissions. **Consequently, constant emissions of CO_2 from any given source will lead to a steady rise in global temperatures as this CO_2 builds up in the atmosphere, whereas constant emissions of methane will not lead to further warming, much beyond that which occurred when the source was first established.**

Awareness of the limitations of GWP_{100} has led to alternative approaches being proposed. These include GWP*, which seeks to better represent the temperature impact of short-lived GHGs by capturing the effect of a change in the rate of emissions (Cain et al., 2019; Lynch et al., 2020). The latest IPCC AR6 report concluded that GWP* gives a better representation of observed changes in global temperatures than GWP_{100} but did not recommend a particular metric. Furthermore, Meinshausen and Nicholls (2022) recently argued that GWP* is essentially a model rather than a metric, as it does not offer the necessary simplicity, transparency, and stability to support climate change negotiations and trading systems. In the context of ecosystem emissions, Neubauer and Megonigal (2015) also argued that GWP metrics which represent the warming impact of a pulse of emissions are not appropriate for emissions from ecosystems which occur steadily over time, and instead proposed the 'Sustained Global Warming Potential' (SGWP) to represent the impacts of a steady emission. Their proposed SGWP for methane of 45 is notably higher than the GWP_{100} value of 27.2. While the GWP* and SGWP approaches appear somewhat contradictory (one discounts steady methane emissions while the other penalises them), a common feature of both methods is that any short-term increase in methane emissions would be expected to have a stronger warming impact than would be implied by using the standard GWP_{100} metric. This clearly has significant implications for activities such as wetland restoration.

Finally, it is worth noting that no global warming metric accounts for the extent to which emissions of methane or any other GHG from natural sources formed part of a stable, pre-human climate system. While emissions reporting protocols seek to take account of baseline (natural or pre-industrial) emissions, the implementation of a GWP-based approach to methane emissions from restored ecosystems remains problematic. **Methane emissions from pristine wetlands, or from restored wetland in which emissions have returned to natural levels, make no contribution to anthropogenically-induced global warming.**

The natural and anthropogenic sources of methane

Given the importance of methane in determining the radiative balance of the atmosphere, there is great scientific community focus on understanding the various contributors to atmospheric methane. The Global Carbon Project publishes frequent updates to the global methane budget (most recently Saunois et al., 2020), which draw on a wealth of data collected at ground level, atmospheric measurements, studies of the isotopes of carbon in methane, and satellite borne instrument retrievals all of which either inform or validate sophisticated numerical models. This effort, involving hundreds of researchers, makes a major contribution to the IPCC reports including the latest published report of Working Group 1 of the 6th Assessment Report (IPCC, 2021). Readers requiring further detail are directed to these works, but we summarise the major contributors to the atmospheric methane budget here as illustrated in Fig. 1.

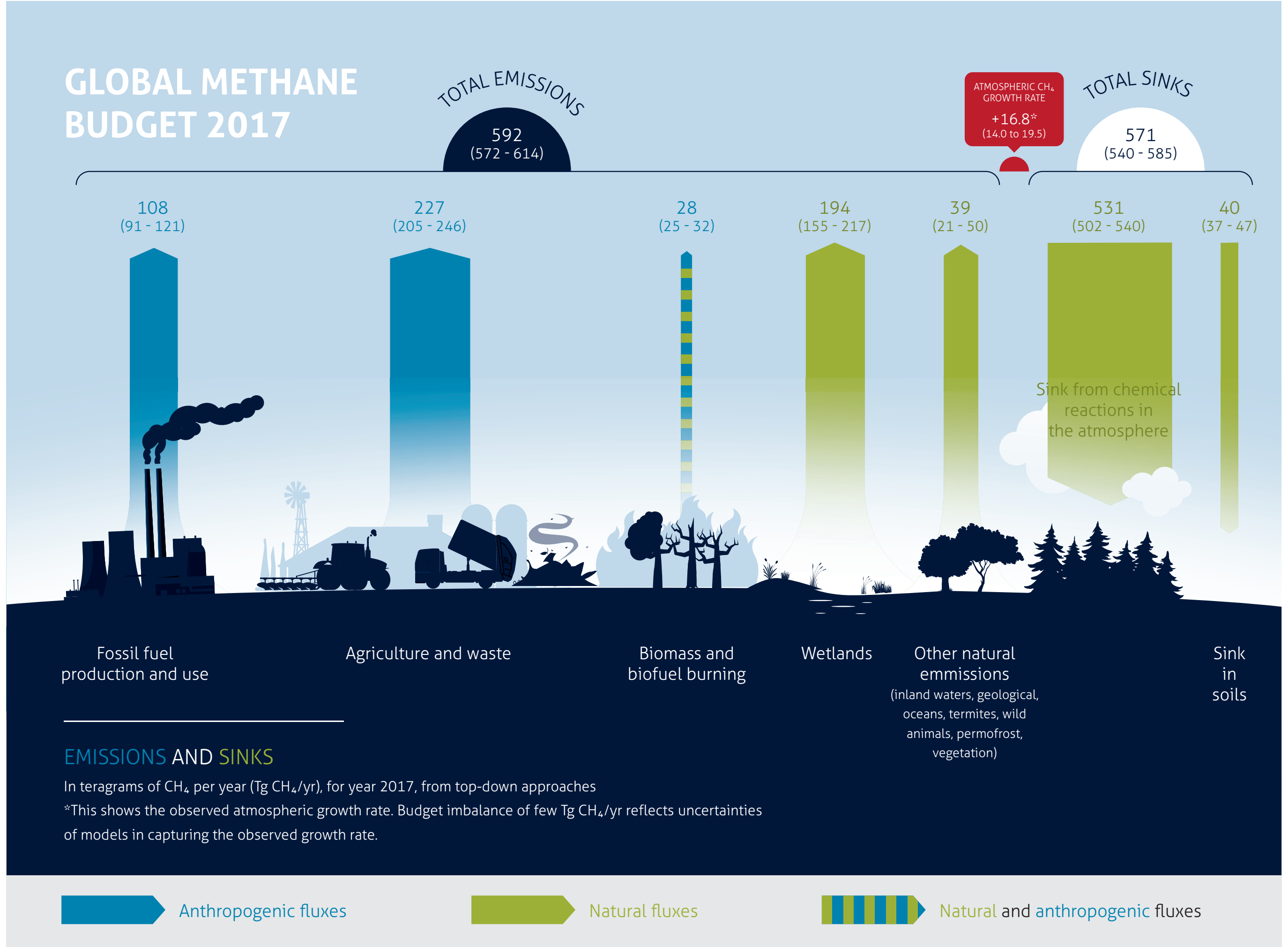

Figure 1*. The Global Methane Budget 2017. The most recent estimate of the global methane budget established via top-down approaches. From Jackson et al (2020) Individually, wetlands are the largest source since agricultural and waste sources are conflated.*

The present-day global methane budget consists of total emissions of 592 Tg (1 teragram = 1012g or 1 million tonnes) each year. This emission exceeds total sinks (principally through atmospheric degradation by hydroxyl ions and other processes) of around 571 Tg yr-1, an imbalance which leads to the observed growth in atmospheric concentrations. In terms of sources, the budget is dominated by anthropogenic emissions (orange arrows in Fig. 1) which derive from a combination of a wide range of sources collectively derived from fossil fuel production (108 Tg each year), as well as agriculture and waste emissions (227 Tg each year). Methane is also produced through biomass and biofuel burning under low oxygen conditions, but in this case, it remains difficult to distinguish between natural and anthropogenic sources since they have an identical carbon isotopic signature in the atmosphere.

In terms of 'natural' emissions, wetlands are estimated to contribute about 194 Tg of methane each year to the atmosphere. These emissions dominated the pre-industrial methane budget and remain significant today.

The role of inland waters as methane emission sources is also ambiguous; top-down estimates of the global methane budget generally consider inland water contributions to be small but bottom up estimates suggest that they may be large, amounting to around 150 Tg of emissions each year (Jackson et al 2020; Rosentreter et al., 2021). This apparent mismatch could in part reflect the fuzzy boundary between inland terrestrial wetlands and inland waters, which often co-occur within the landscape and can fluctuate in their relative extent through the year, as well as ambiguous definitions of the respective categories in some bottom-up studies which may have led to double-counting.

Other natural sources of methane to the atmosphere include geological sources, oceans, termites, wild animals, and vegetation. Most of these sources are relatively small, and the global methane budget estimates that the sum of all non-wetland sources (here including inland waters) is just 31 Tg per year, i.e., only 20% of the wetland emission. With wetland contributions to the atmospheric methane burden being the focus of this report, we now discuss in detail on the processes that lead to methane emissions from wetlands, the relative importance of different wetland types, and the changing contributions of wetlands to the global methane budget in response to anthropogenic change.

Box 1:
Defining wetlands

To understand the role of wetlands in the global methane budget, it is important to understand the different categories of wetland that exist, and their different roles in the methane cycle. Unfortunately, there are overlapping definitions of wetlands in both the scientific literature and international conventions. The definition of 'wetlands' is also somewhat ambiguous, both in the scientific literature and in international conventions.

The Ramsar Convention defines wetlands as "Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". It identifies three broad categories: <u>Marine/coastal</u> wetlands include intertidal wetlands such as mangroves and salt marshes, as well as sub-tidal habitats such as kelp and sea-grass beds; <u>Inland wetlands</u> include peatlands and inland wetlands on mineral soil, as well as other inland waters (lakes, streams, ponds etc.); and <u>human-made wetlands</u> include irrigated land, constructed ponds, ditches and reservoirs.

The IPCC Wetland Supplement (IPCC, 2014) considered emissions from peatlands, inland wetlands on mineral soil, coastal wetlands, and constructed wetlands, with the subsequent IPCC Inventory Refinement (IPCC, 2019) adding methods to report emissions from 'Flooded Lands', namely reservoirs and constructed waterbodies such as ponds and ditches.

For the purposes of this report, we need segregation into functional units with respect to methane without creating a new classification system. We subdivide the Ramsar 'inland wetland' category into two units 'inland terrestrial wetlands' (i.e., wetlands on organic and mineral soils) and 'inland waters' (lakes, streams, ponds etc.). Inland terrestrial wetlands are further disaggregated into peatlands and inland wetlands on mineral soil where appropriate. The reason for this subdivision is that methane emissions vary between these functional units.

How is methane released from wetlands?

The amount of methane released from wetlands to the atmosphere is governed by several processes. These include the processes of methane production and in situ consumption, which in turn are determined by a range of factors. The latter include: 1) the oxygen content of the soils or sediments; 2) the availability and quality of methanogenic substrates (i.e. organic matter used as a microbial energy source); 3) the availability of alternate electron acceptors that can divert substrate degradation away from methane production; and finally 4) the means of escape to the atmosphere, which determines the duration of transit from the zone of production to the point of release, and therefore the extent to which methane removal processes can operate.

Methane is produced by a group of micro-organisms known as methanogens (or methane-producing archaea) under strict absence of oxygen (Conrad, 1989). Methane formation is the terminal and lowest energy-yielding step of carbon degradation in anaerobic systems, after other electron acceptors (i.e. oxidising compounds) such as nitrate, ferric iron, and sulphate have all been consumed. As a consequence, brackish or saltwater wetlands, or those overlying sediments rich in sulphates, tend to be lower emitters of methane than inland terrestrial wetlands since these systems decompose substrates via sulphate reduction more than via the reduction of organic matter with consequent methane production (e.g. Reeve et al., 1996). Indeed the input of sulphate to wetlands via pollutant deposition in acid rain, may have led to reduction in methane emissions during much of the 20th Century (Gauci et al., 2004). As with all biological processes, temperature governs the rate at which the relevant processes take place with the largest rates of methane emission typically found in the tropics (Pangala et al., 2017).

Critically, however, the extent of methane emission from wetlands depends not only on the rate of methane production, but also on how much of this methane is consumed before it reaches the atmosphere. This in turn depends on the means of transfer from the zone of production to the atmosphere, which determines the extent of methane exposure to the action of methane oxidation by methanotrophic bacteria. Key pathways for methane emission are summarised in Figure 2. Methane oxidation mostly occurs under aerobic conditions, so it is able to take place above the water table and in the root zone of wetland sediments, or within an overlying oxygenated water column. In all of these settings, methanotrophy can consume the majority of produced methane, such that slow (diffusive) emissions across the soil-atmosphere and aquatic-atmosphere boundaries tend to form only a minor contribution to overall wetland methane emissions (Carmichael et al., 2014). On the other hand, gas transport pathways that effectively bypass the aerobic zone can lead to high emissions. Ebullition, or bubbling, is a highly spatially and temporally variable process, often involving abrupt and localised episodic events, which can transfer methane from the anaerobic zone to the atmosphere. Additionally, plants adapted to growing in wetland conditions possess adaptations such as hollow aerenchyma tissue, that allow oxygen to reach their roots, thus maintaining healthy root function in an otherwise inhospitable environment and permitting rhizosphere methane oxidation. These same tissues also permit methane to be transported in the other direction, from the root zone to the atmosphere, with relatively little impedance from methanotrophy.

Until recently, herbaceous plants such as reeds and sedges were thought to be the only major vegetation emission source from wetlands. However, evidence has been collected over the past decade to demonstrate that trees also act as important pathways for wetland-produced methane, in both tropical and high-latitude regions. For example, trees in the Amazon floodplain were found to contribute half of all methane emitted from the region (around 20 Tg each year; Pangala et al. 2017) and trees in southeast Asian peat swamp forests were found to dominate emissions over other emission pathways (Pangala et al., 2014). Gauci et al (2022) have estimated that trees contribute 43.5 Tg of the total annual tropical wetland source of 96 Tg of methane. That said, there is evidence that in some highly emitting wetland trees, methanotrophs can attenuate up to 30% of emissions (Jeffrey et al., 2021)

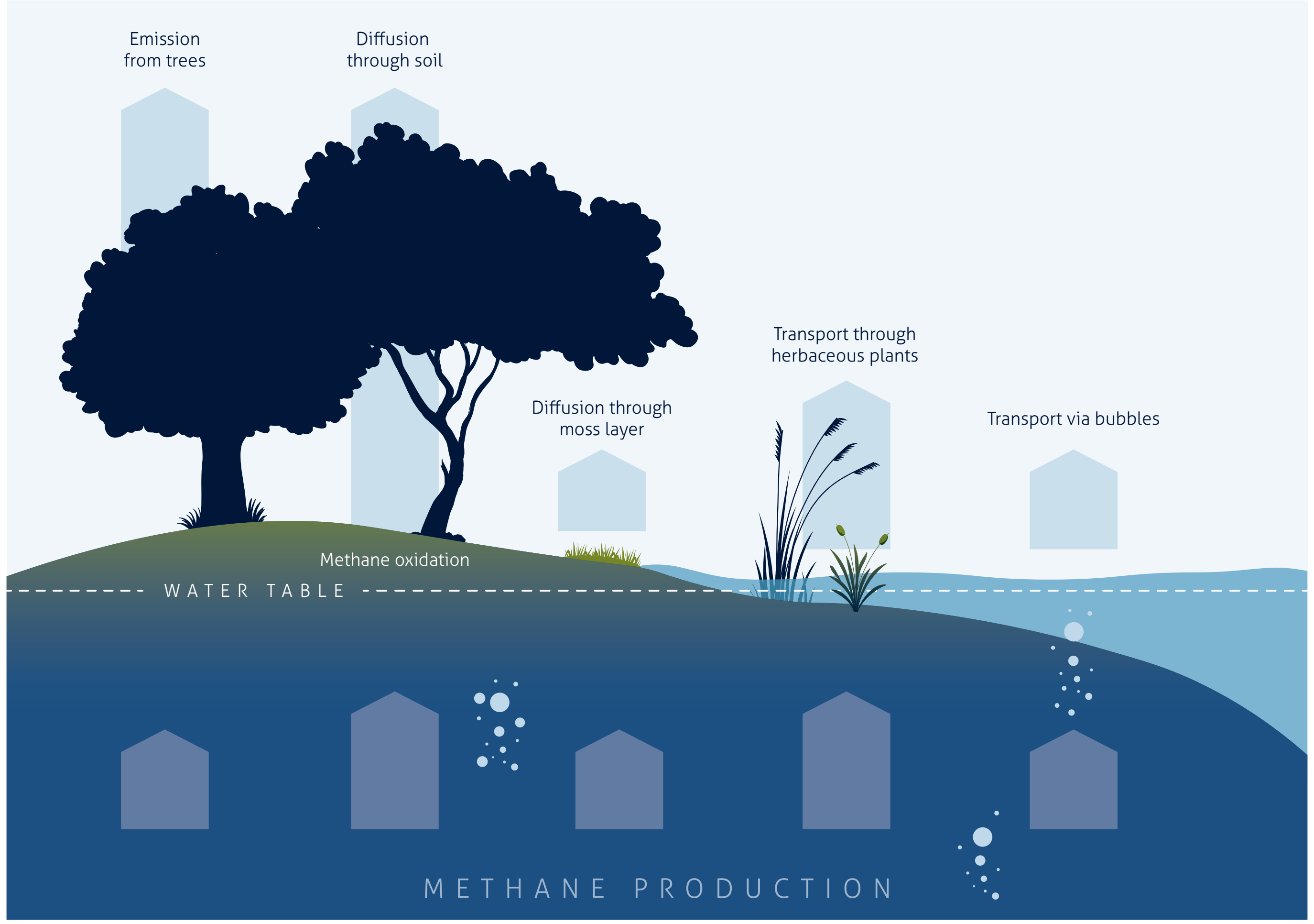

Figure 2. *Pathways of methane production, transport and removal in wetland ecosystems*

While many higher plants can facilitate methane transport to the atmosphere, there is evidence that some mosses, notably Sphagnum and brown mosses, can have the opposite effect by hosting symbiotic methanotrophic bacteria on their leaves or within cells (Raghoebarsing et al., 2005; Liebner et al., 2011; Holland-Mority et al., 2021). This process simultaneously reduces wetland methane emissions and increases carbon supply to the plants, facilitating long-term carbon sequestration through peat formation. Effectively, Sphagnum and other moss carpets on wetlands may therefore act as methane filters.

Following wetland drainage, IPCC emissions reporting methods initially assumed methane emissions would drop to zero, on the basis that little if any methane produced at depth would reach the atmosphere through a deep aerobic zone (IPCC, 2006). This appears to be broadly true in relation to the terrestrial part of drained wetlands, with emissions falling to near-zero values (or even slight net uptake of atmospheric methane by soil methanotrophs) when average water table depths fall below around 20-30 cm (Evans et al., 2021). However, wetland drainage generally requires the creation of ditch networks, which are now known to act as hotspots of methane emission via lateral transport of methane from the soil, or direct production within anoxic sediments in the ditches themselves (Evans et al., 2016). Emissions from wetland ditches are now included in IPCC emissions inventory methodologies (IPCC 2014, 2019) and Peacock et al. (2021a) estimate that global methane emissions from wetland ditches lie in the range 0.6 to 10.5 Tg yr^{-1}. Clearly, wetland drainage does not reduce overall methane emissions to zero.

Contribution of different wetland types to global methane emissions

Rosentreter et al. (2021) recently evaluated the total contribution of aquatic ecosystems to global methane emissions, which we summarise here. We use their median values, which sum to a total emission of 269 Tg per year (higher than the wetland emission estimate in the Global Methane Budget but in the same range) rather than their mean values, which sum to 431 Tg per year and appears difficult to reconcile with the top-down emissions estimate of Saunois et al. (2020). The definition of aquatic ecosystems used by Rosentreter et al. is broad, and roughly aligns with the Ramsar approach. It includes inland terrestrial wetlands; a range of inland waters (streams, rivers, lakes, ponds, reservoirs); areas under cultivation for rice and aquaculture; coastal ecosystems (estuaries, mangroves, saltmarshes, seagrasses, tidal flats); and the ocean.

The overall attribution of methane emissions by aquatic ecosystem type is shown in Figure 3. According to this analysis, inland terrestrial wetlands (including wetlands on both organic and mineral soils) are responsible for 55% of total emissions (150 Tg per year). Lakes contribute 20% (56 Tg per year), with the highest emissions from the smallest waterbodies (i.e., ponds). Human-made wetland types (rice paddies, reservoirs, and aquaculture ponds) collectively contribute a further 18% (50 Tg per year), while coastal wetlands contribute just 2% (5 Tg per year).

While these estimates clearly carry a high degree of uncertainty, as the authors acknowledge, we can nevertheless draw some general conclusions:

1) Inland terrestrial wetlands are the single most important contributor to overall methane emissions from aquatic systems, and to the global methane budget.

2) Naturally occurring inland waters are also an **important methane source** (and may be considered wetlands- as in Ramsar Convention-, though definitions are not always consistent in the literature. See Box 1).

3) Coastal wetlands (and indeed the oceans) are rather **minor sources of methane**, consistent with the role of sulphate in seawater suppressing methane production as discussed above.

4) Human activities have greatly **increased methane emissions** from aquatic ecosystems. The 50 Tg per year attributed to rice cultivation, reservoirs and aquaculture omits some additional constructed waterbodies with high methane emissions such as farm dams and ditches (Peacock et al., 2021a, 2021b), in addition to which anthropogenic activities such as agricultural and wastewater pollution have greatly modified methane emissions from some naturally occurring wetland ecosystems. **Characterisation of the entire wetland emission in the Global Methane Budget as a 'natural flux', separate to the anthropogenic 'agriculture and waste' flux (Figure 1) (both of which clearly have an impact on wetland methane emissions) could therefore be considered to give a slightly misleading impression of the overall role of global wetlands as emission sources.**

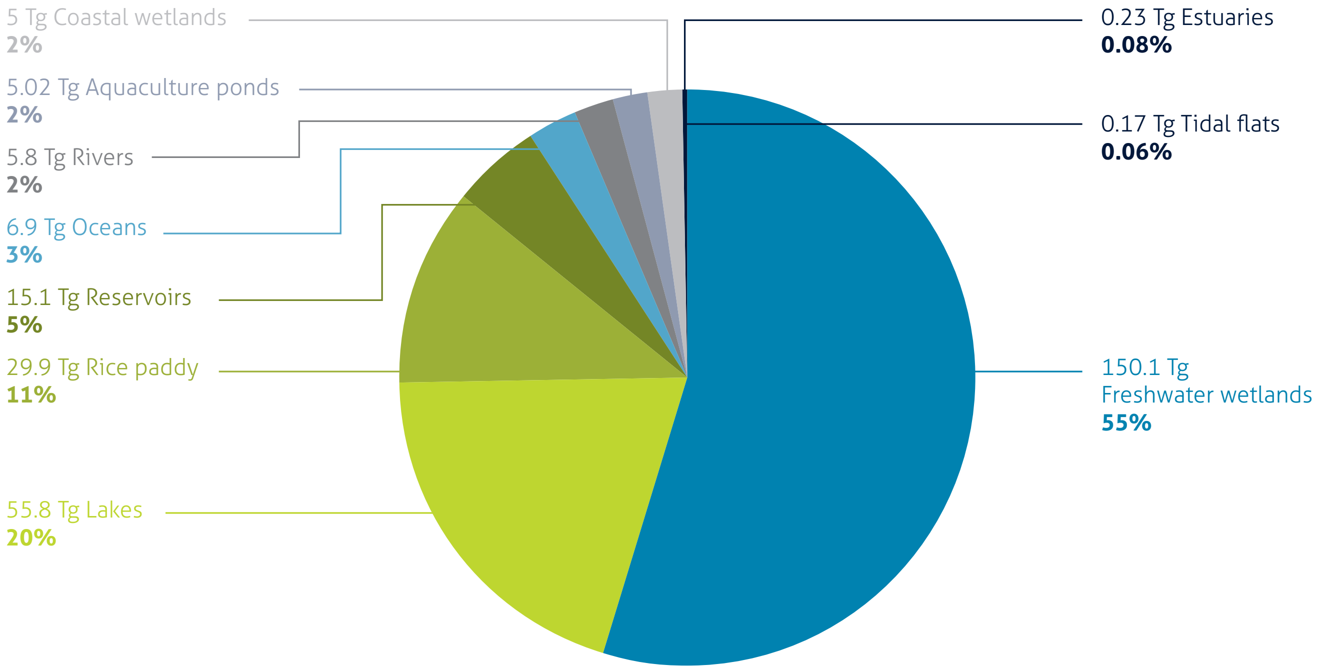

Figure 3. *The contribution of different natural and human-made ecosystem types to total methane emissions from aquatic ecosystems, as estimated by Rosentreter et al. (2021). Upper figures show the annual emission in Tg, lower figures the percentage of total wetland emissions attributable to this source. Naturally occurring ecosystem types are shaded blue, human-made ecosystems are shaded yellow. Note that methane emissions from naturally occurring systems can also include an anthropogenic component.*

Northern Rufiji Delta, Tanzania.
By Menno de Boer, Wetlands International

The contribution of wetlands to atmospheric methane through time

Wetlands have been the dominant source of methane emissions throughout most of Earth's history, a situation which only changed following the industrial revolution. Insight has been gained on past atmospheric methane concentrations through a combination of monitoring stations that have established monthly mean atmospheric concentrations since the early 1980s (see https://gml.noaa.gov/ccgg/trends_ch4/), and high-resolution records for the last thousand years derived from firn snow prior to ice closure (Etheridge et al., 1998). Deeper still, ice core records that extend ~800,000 years before the present day give insights into the Pleistocene atmosphere spanning multiple ice ages (Loulergue et al., 2008) and modelling studies provide estimates of atmospheric methane spanning millions of years (Beerling et al 2009). In all but the most recent century, wetlands are considered the principal source of emissions, although there may have been periods when geological sources such as release of marine methane hydrates were more important.

The Quaternary period (Pleistocene and Holocene) provides the nearest baseline against which the modern methane cycle can be compared. During glacial maxima, lowered sea levels, aridity, cooling, and low ambient CO_2 concentrations are likely to have all influenced wetland emissions, sometimes in contrasting ways (Kaplan 2002; Hopcroft et al., 2017; Boardman et al., 2011). For example, dry glacial conditions may have limited continental wetland extent, but the exposure of flat continental shelves by low sea levels (as water was locked into ice caps) could have provided additional space for wetlands, which were then submerged during interglacials (including the current Holocene period). Changes in ice cap and permafrost extent may also have affected methane emissions from high-latitude and high-altitude wetlands, but overall impacts are hard to predict, with wetland extent likely decreasing in some areas, but expanding in others. Overall, however, ice core data indicate that atmospheric methane concentrations have been lower during cold, dry glacial periods, and higher during warmer, wetter interglacials (Loulergue et al., 2008).

During the Holocene period, human activities have altered the role of wetlands as methane sources. Their small-scale mid-Holocene conversion to early rice agriculture across Asia may have been the first direct way humans modified Earth's climate (the so called Early-Anthropocene Hypothesis, Ruddiman 2003). Given the implications of the hypothesis, the idea has received much scrutiny (e.g., Singarayer et al., 2011) and remains debated. Since the onset of industrialisation and the associated expansion of human populations and demand for agricultural land, there has been a clear trend towards declining wetland extent. Some studies suggest very high rates of loss; for example, Davidson (2014) estimated that 87% of global wetland area may have been lost since 1700. However, a more recent estimate suggests a total loss of 3.4 million km2 during this time, equating to 21% of the original wetland area (Fluet-Chouinard et al., 2023). Rates of wetland loss were highest in the mid-20th century, and occurred mainly in Europe, the United States and China. Causes of wetland loss include drainage and conversion to dryland agriculture and forestry, development of rice paddies, urban and infrastructure development, flood protection, resource exploitation and coastal land reclamation. The two largest drivers of wetland loss are believed to have been cropland and rice paddy development (Fluet-Chouinard et al., 2023).

Based on these figures, there has probably been a modest decline in methane emissions from natural wetlands since 1700, with most of the change having occurred in the last 100 years. However, this decline has been counterbalanced by rising methane emissions from rice paddies and other constructed wetlands; drainage ditches acting as methane hotspots within drained wetland landscapes (Peacock et al., 2021a); and the effects of eutrophication. These human impacts on the methane cycle are discussed in the following section.

Bulacan's Intertidal Zones, Philippines. By Danica Uy

Natural versus anthropogenic wetland methane emissions

As described above, wetlands naturally emit methane. Prior to the onset of human influence, methane emissions from wetlands formed part of a natural cycle, in which both atmospheric methane concentrations and the climate were stable. Human activity has modified the processes that cause wetlands to produce methane in several ways, some of which are illustrated in Figure 4. Firstly, the destruction and drainage of wetlands has reduced methane emissions below natural baseline levels in the areas where it has occurred (Figure 4a). While this may have had some offsetting impact on the scale of atmospheric methane increases associated with other activities such as fossil fuel use, waste and ruminant livestock agriculture, it has typically been accompanied by the oxidation of wetland carbon stores and resulting emission of CO_2. **In many wetlands this CO_2 increase far exceeds any 'beneficial' impact of reduced natural methane emissions.** For example, based on the UK data presented by Evans et al. (2021), a peatland drained to a depth of 80 cm can be expected to emit CO_2 with a 100-year climate warming impact (depending on whether GWP_{100} or $SGWP_{100}$ is used) between 2.9 and 4.6 times larger than any cooling effect of lower methane emissions. Also, as noted earlier, methane emissions do not fall to zero in drained wetland landscapes, due to the presence of drainage ditches which act as methane emission hotspots (Peacock et al., 2021a). **In short, draining wetlands lowers the baseline CH_4 emissions but strongly increases the CO_2 emissions.**

Restoring and re-wetting wetlands has the potential to reverse these changes by halting carbon loss, or even turning the wetland back into a net carbon sink, while raising methane emissions back towards natural baseline levels. Again, for a deep-drained wetland it is likely that re-wetting will, over longer time horizons, have a net cooling impact on the climate. Based on the same Evans et al. data used in the example above, re-wetting would lead to a net reduction in the combined warming impact of CO_2 and methane until water levels are within 8 cm of the surface based on GWP_{100}, and within 12 cm of the surface based on $SGWP_{100}$ (i.e., choice of long-term metric makes rather little difference to optimal water level management from a climate perspective). Concerns are sometimes raised that wetland re-wetting could generate a short-lived 'spike' of methane emissions, taking them above natural baseline levels (red line in Figure 4a) but evidence for this is inconsistent, and it may depend on the former land-use (for example the level of soil nutrient enrichment) as well as the nature and effectiveness of restoration.

As a related issue, and as discussed earlier, some global warming metrics penalise step-change increases in methane emissions by assigning a high warming impact in the decades following this change. This could be construed as an argument against wetland restoration, although the logic of applying metrics designed to quantify pollutant impacts to a reinstated natural flux seems questionable. Equally, it could be argued that the transient warming impacts of increased methane mean that wetland restoration needs to occur sooner rather than later, in order that these short-term impacts can work through the atmosphere before further CO2-driven warming occurs. This argument is particularly strong in the case of wetlands with large ongoing CO_2 emissions (Günther et al., 2020). Of note here are tropical peatlands, which are among the largest sources of land-use CO_2 emissions in the world when drained, but which emit only relatively small amounts of methane when wet (in their natural state or when restored) (Deshmukh et al., 2020).

A second human impact on wetland methane emissions can occur because of increased inputs of pollutants to the ecosystem. Elevated inputs of reactive organic matter such as human or animal wastes can increase substrate availability for methanogens, and lead to greater oxygen depletion within wetland soils and waters, favouring anaerobic methane production over aerobic decomposition. Inputs of nutrients such as nitrogen and phosphorus from agriculture or wastewater either directly to a wetland or via upstream watercourses, can similarly lead to higher productivity which can in some cases (for example algal blooms in wetland waterbodies) increase organic matter loadings and oxygen depletion, again favouring methane release. As shown in Figure 4b, this has the potential to raise methane emissions above natural baseline levels, in some cases very substantially. For example, the recently published IPCC 'Flooded Lands' methodology (IPCC, 2019) estimates that methane emissions from heavily nutrient-enriched (hypereutrophic) reservoirs may be 36 times higher than those from the most nutrient-poor (oligotrophic) reservoirs. Construction of human-made wetlands including rice paddies, aquaculture ponds and farm dams also make a major contribution to global methane emissions, as discussed above. Since these emissions can (to the extent that they exceed the natural baseline) be considered anthropogenic, there is a strong case for mitigating these excess emissions through measures such as controls on nutrient and organic matter loadings to both natural and constructed wetlands.

Drainage ditch, Iceland. By Chris Evans

Impact of future climate change on wetland methane emissions

Considerable concern has been expressed about the potential future role of climate change in increasing methane emissions from natural wetlands, raising the possibility of a positive feedback (whereby greater climate warming leads to greater wetland methane emissions, leading to further warming; Figure 4c). Mechanisms by which this could occur include increased wetland extent through changes in rainfall patterns, permafrost thaw, and the direct impact of higher temperatures and atmospheric CO_2 levels on the plant and microbial processes that lead to methane production. Several recent papers have modelled the impact of these feedback processes, and suggested that wetland emissions could increase by 50 to 150% by the end of the century (e.g. Shindell et al., 2004; Ringeval et al., 2011; Gedney et al., 2019; Zhang et al., 2017; Koffi et al., 2020), albeit often based on 'worst-case' climate scenarios (e.g. RCP8.5) that are no longer considered likely (Pielke et al., 2022). The authors of these studies generally conclude that, because of this anticipated feedback, reductions in anthropogenic greenhouse gases will need to exceed those currently planned to achieve global targets for limiting temperature increases. While the climate-wetland feedback is certainly a cause for concern, it should be emphasised that the magnitude and even the direction of wetland methane responses to climate change are uncertain and may vary between regions. For example, permafrost thaw could increase the extent of wetlands in some regions, but by increasing the amount of groundwater versus surface flow (Frey and McClelland, 2009) could reduce wetland extent elsewhere. The impacts of climate change on rainfall patterns and associated wetland extent are also uncertain, and likely to vary regionally. Finally, a positive methane response to higher temperatures may depend on the pathways by which this methane is transported to the atmosphere, and whether methanogens are more responsive to higher temperatures than methanotrophs (Dean et al., 2018). As an example of the risks inherent in inferring a simple temperature dependence on methane emissions, recent fluxes measured over an intact tropical peat swamp forest (mean temperature of 27 °C) were found to be not greatly different from those of temperate and boreal bogs with mean temperatures of < 10 °C (Deshmukh et al., 2020). Consistent with this, Rosentreter et al. (2021) found no clear latitudinal variations in methane emissions from a range of aquatic ecosystems based on their review of published data and considered levels of anthropogenic disturbance (as well as ecosystem type) to be a more important driver of variation.

Overall, the balance of evidence suggests that global wetland methane emissions may increase in response to climate change, but comparisons with observations suggest that the magnitude of this response may be at the lower end of current model predictions (Ma et al., 2021). Realistically, the only way to mitigate this feedback will, as has been suggested previously, be to minimise climate change through reduced emissions of CO_2, methane, and other greenhouse gases from anthropogenic sources. Larger and more hydrologically intact wetland ecosystems may also be less susceptible than damaged and fragmented ones to the climate change impacts that result in higher methane emissions.

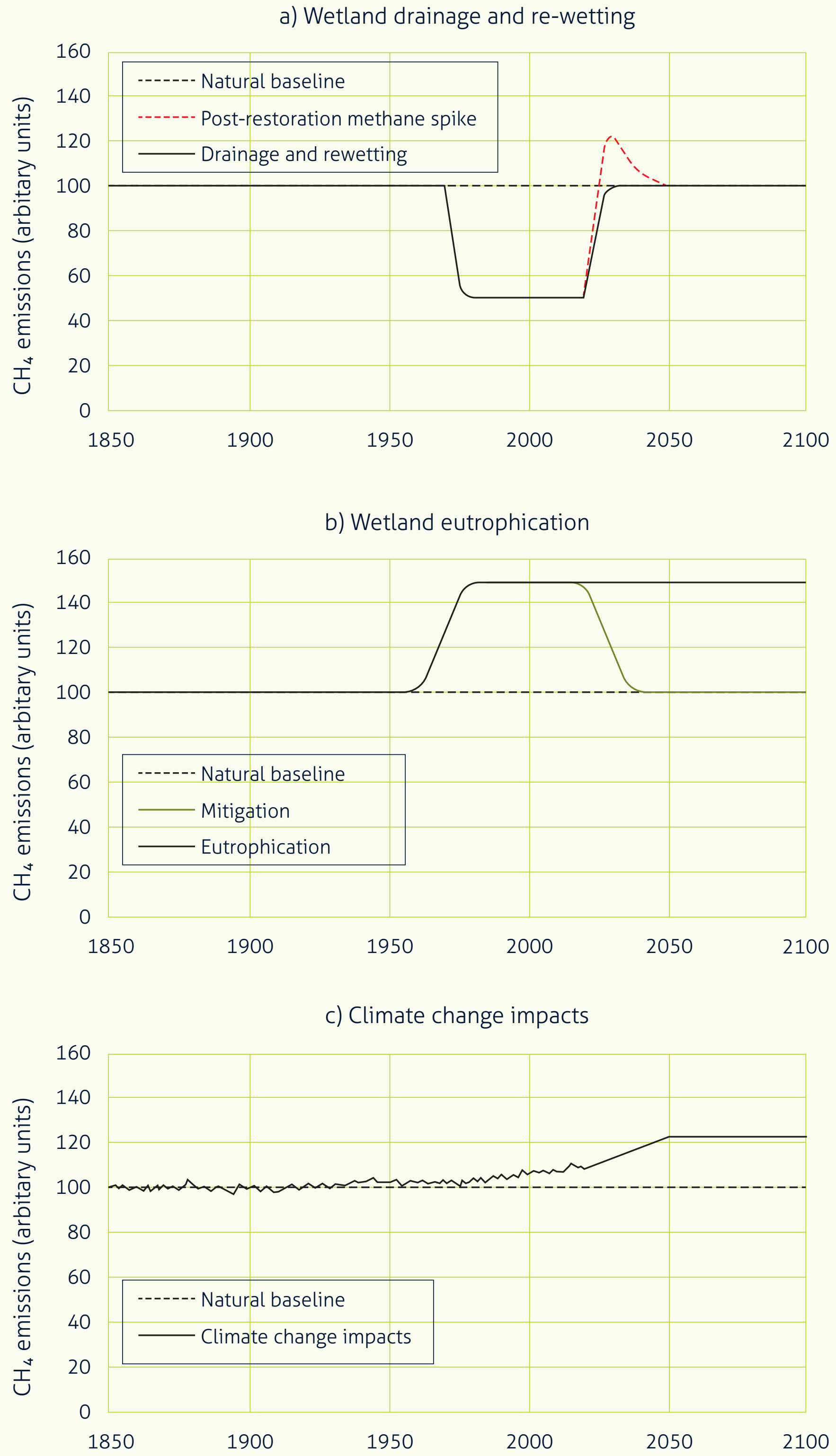

Figure 4. *Illustrative examples of human impacts on wetland methane emissions: a) effects of wetland drainage and re-wetting, including a potential 'methane spike' after re-wetting; b) effects of wetland eutrophication by nutrient and organic matter pollution, including potential mitigation impacts; and c) potential impacts of climate change on emissions from natural wetlands. Panels a) and b) are purely conceptual, panel c) is based on the global temperature anomaly from 1850, a projected warming of 2 °C by 2050 based on the RCP2.6 scenario, and a Q10 temperature response function of 2.6 set to approximately reduce the projected increase in wetland methane emissions predicted under this scenario by Zhang et al. (2017).*


Training by Mangrove Action Project on Ecological Mangrove Restoration in Rufiji Delta, Tanzania. By D. Wodehouse.

Mitigating anthropogenic methane emissions from wetlands

As discussed above, wetland methane emissions may have been influenced (both positively and negatively) by human activities, but the overall magnitude of change versus pre-industrial levels is difficult to quantify. It is however likely that most of the methane emitted to the atmosphere by wetlands each year is natural, and that total emissions were higher in the past when wetland extent was greater. This does not however preclude a substantial anthropogenic component of current 'wetland' emissions because of activities including rice cultivation, eutrophication, organic pollution, and the construction of some high-emitting wetland types such as farm dams. It is therefore likely that **a component of present-day wetland emissions could be mitigated through improved management and restoration.**

While some anthropogenic wetland methane emissions may be mitigated, this should in no way be taken as an argument for wetland destruction as a climate mitigation measure. Remarkably, this has occasionally been suggested; for example, Muller (2019) argued that loss of natural floodplain wetlands could be considered part of the overall climate benefit of hydroelectric dam construction. The recent attribution of surging atmospheric methane concentrations to wetter conditions in large African wetlands (Lunt et al., 2019) has also raised concerns that the perceived climate benefits of lower methane emissions could become part of the justification for development projects. For example, the unfinished Jonglei canal through the Sudd wetland in South Sudan would, if completed, divert the flow of the White Nile with the aims of reducing floods, generating hydropower, and facilitating agriculture by increasing downstream flows (Conflict and Environment Observatory, 2021; Pearce, 2022). Whether in the Sudd or elsewhere, the consequences of such actions for wetland carbon stores, as well as for biodiversity, regional weather patterns and wider sustainability, could be catastrophic. Furthermore, **given the differences in their atmospheric lifetimes, the sustained warming impacts of CO_2 released from such activities would extend far beyond the transitory cooling impact of any reduction in methane.**

While proposals to reduce global methane emissions by draining intact wetlands thankfully remain rare, concerns about the potential methane impact of re-wetting already-drained wetlands are widespread. As noted earlier, there is to some degree an unavoidable trade-off between methane and CO_2 emissions, leading to what has been termed a 'methane cost' of wetland restoration (Hemes et al., 2018). This 'cost' is not fixed, however; it will be highest where restoration leads to a 'methane spike', for example where a large pool of agricultural nutrients and labile organic matter remain in the ecosystem to drive enhanced methane production; where restoration results in dominance of methane-transporting aerenchymatous plants rather than methane-filtering species such as Sphagnum; or where it creates pools of shallow standing water with emergent plants that favour high rates of methane emission (Calabrese et al., 2021; Evans et al., 2021). Concerns about methane are therefore not an argument against wetland restoration, but an argument in favour of ***best practice restoration***, which creates the hydrological, biogeochemical, and ecological conditions that favour CO_2 sequestration whilst minimising methane emissions.

'Best practice restoration' will depend on reality, depend on local conditions and circumstances. Raising water levels in drained wetlands is unlikely to generate any significant methane emissions until water levels are within 20 cm of the surface (Couwenberg et al., 2011; Evans et al., 2021), although this water level may not entirely halt CO_2 emissions. Removing nutrients either before or during the early stages of restoration, for example via the cultivation of productive paludiculuture crops with a high nutrient demand, may help to overcome the effects of historic nutrient pollution. In wetlands that have not been drained but which have been affected by other human activities such as nutrient and organic matter pollution, interventions that reduce these pollutant inputs will deliver a clear climate mitigation benefit by reducing artificially high rates of methane emission, as illustrated in Figure 4b. In coastal wetlands where methane emissions are suppressed by high concentrations of sulphate (including saltmarshes, mangroves and some peatlands that developed under brackish conditions or were subsequently inundated by seawater), any restoration is likely to deliver benefits for CO_2, with only negligible methane emissions, and similarly there is evidence that adding sulphate to constructed wetlands such as rice paddies may help to suppress methane emissions (Gauci et al., 2008). Other means of suppressing methane emissions from constructed, cultivated or restored wetlands could include optimised water and nutrient management, and the application of amendments to reduce methane emissions such as biochar, but many of these methods remain to be tested.

Positive feedbacks between climate change and natural wetland methane emissions should be considered effectively 'unmitigatable', other than by reducing the anthropogenic GHG emissions that are leading to climate change. However, we consider that the impacts of warming on wetland methane emissions may be relatively modest (and perhaps lower than some modelling studies have predicted), at least in the near term.

Finally, where wetland restoration does occur, there is a strong argument for doing it sooner rather than later. Günther et al. (2020) modelled the climate forcing impact of a range of scenarios including continued peatland drainage, immediate re-wetting, and postponed re-wetting. Under the drained scenario, CO_2 continues to be emitted and accumulates in the atmosphere. Re-wetting halts this CO_2 emission immediately and may even convert the peatland back into a net CO_2 sink; in either case, the cumulative warming impact of continued drainage is avoided. Increased methane emissions after re-wetting lead to short-term warming, but due to its short atmospheric lifetime this effect plateaus within around two decades, whereas the warming impact of continued CO_2 emissions from a drained peatland continues, potentially until the entire peat mass has been oxidised. While restoration may generate some short-term warming, therefore, this is far smaller than that which would occur under a counterfactual of continued drainage (Figure 5). Achieving 2050 Paris Agreement temperature targets by minimising short-term methane emissions from wetlands at the expense of longer-term CO_2 emissions would therefore achieve little; as Günther et al. note, "Warnings against methane emissions from rewetted peatlands are therefore unjustified in the context of effective climate change mitigation". While the study was specific to peatlands, the same conclusions could be drawn for any drained, carbon-rich wetland soil. The sooner all drained wetlands are re-wetted, the lower the probability of overshooting temperature targets in the long term.

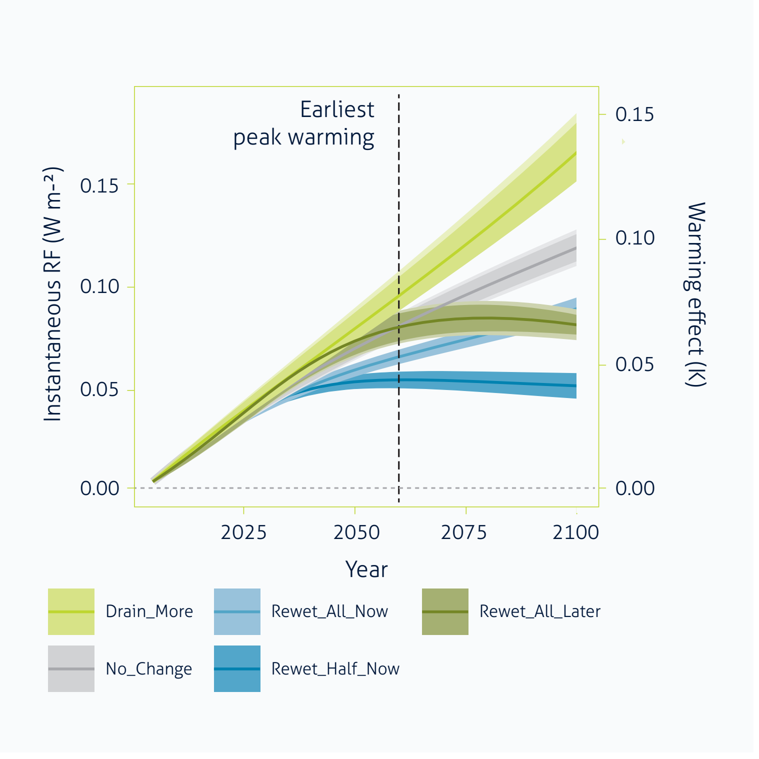

Figure 5. *Modelled radiative forcing (RF) and warming effect of five scenarios for the future management of global peatlands, taking account of long-term CO2 emissions from drained peatlands and higher methane emissions following re-wetting. From Günther et al. (2020).*

Policy summary

Methane is a powerful greenhouse gas, which is produced by organic matter decomposition in the absence of oxygen. Methane is the second most important contributor to atmospheric warming, being responsible of around 0.5 °C of warming, versus around 0.76 °C warming from CO2 . If we want to limit temperature increase to 1.5 °C above pre-industrial levels, efforts should also address human-induced methane emissions. Main sources of anthropogenic methane emissions include fossil fuel production, agriculture (i.a. ruminant livestock), waste emissions and to some extent burning of biomass and biofuel under low oxygen conditions.

When it comes to wetlands, we need to distinguish **natural methane emissions from anthropogenic or human-induced wetland methane emissions[2].** Unfortunately, it has been suggested on some occasions that methane emissions may be mitigated through the destruction of wetlands: **Wetland drainage or degradation should in no way be taken as a climate mitigation measure.**

Wetlands emit methane as part of their natural functions. Wetlands are the largest natural source of methane emissions to the atmosphere. Emissions from wetlands in their natural state have formed part of a broadly stable global carbon cycle and climate system (the same is true of natural wetland carbon sequestration). **Methane emissions from natural wetlands did not and do not drive anthropogenic climate change.**

Inland wetlands, including both terrestrial and open water wetlands, are the largest sources of wetland methane emissions, with **tropical wetlands** believed to make the largest overall contribution, whereas coastal wetlands make only a minor contribution to methane emissions. Global temperature and atmospheric CO_2 increases could accelerate the natural processes that lead to methane emissions from wetlands, however, more research and improved data are needed.

Human activities such as agricultural and wastewater pollution have greatly modified methane emissions from some naturally occurring wetland ecosystems. As a result, a part of the methane emission from 'natural' wetlands, as reported in the Global Methane Budget, is not natural, but human-induced. Human-made wetlands such as rice paddies, reservoirs, farm ponds and ditches for wetland drainage are examples of human induced sources of methane emissions. Ditches networks, for instance, are hotspots of methane emissions. Clearly, wetland drainage does not reduce overall methane emissions to zero.

Short-term changes in emissions from wetland **restoration** can result in short-term increases in methane emissions as the ecosystem recovers its natural function (and creates the conditions that enable wetlands to continue sequestering and storing soil carbon).

Next to human-induced methane emissions from wetlands, large-scale loss and degradation of wetlands

[1] Other GHGs contribute to 0.24 °C warming. We have not reached the threshold of 1.5°C because other gases emitted to the atmosphere through human activity, such as sulphur dioxide and nitrogen oxides, have had a counterbalancing cooling effect.

[2] In general, GHG emissions are categorized into anthropogenic and natural. If for instance, a wetland is restored, related emissions are labelled as anthropogenic because there was a human intervention. If a wetland has never been managed, related emissions are considered natural. UNFCCC deals with anthropogenic emissions. However, there can be some overlap or grey areas between natural and anthropogenic emissions, for instance, when wastewater pollution impacts wetland methane emissions.

has had wide-ranging negative environmental consequences, including the release of vast quantities of long securely s**tored carbon in wetlands soils to the atmosphere as CO_2. The long atmospheric lifetime of CO_2** (centuries) compared to methane's (around 10 years) means that the sustained warming impacts of wetland drainage far exceed any transient cooling impacts of lower methane emissions. The **long-term benefit of restoring wetlands and securing millennia stored wetland carbon will undoubtedly outweigh the initial methane peak during restoration.**

Conservation of wetlands should be first global priority, as this keeps carbon stored and methane emissions at natural levels. We also need to strengthen efforts to reduce and avoid pollution penetrating these ecosystems. However, once a wetland has been affected or degraded by different human activities (for instance, agriculture, urban settlements, dams, etc.), rapid deployment of context specific 'best practice' restoration approaches to wetlands will safeguard long-term carbon stores and provide sustained long-term climate benefits with only a modest and short-lived methane cost. The anthropogenic component of present-day wetland emissions could be mitigated through optimised water and nutrient management, pollution controls, and potentially other interventions such as application of biochar, but many of these methods remain to be tested. The sooner wetlands are restored, re-wetted in the case of peatlands, the stronger the net climate benefits will be.

Biodiverse healthy and resilient ecosystems play an important role in strengthening our response to climate change, while providing multiple benefits.

Mangrove Capital Africa in Saloum Delta, Senegal. By Wetlands International.

References

Beerling, D., Berner, R.A., Mackenzie, F.T., Harfoot, M.B. and Pyle, J.A., 2009. Methane and the CH4 related greenhouse effect over the past 400 million years. American Journal of Science, 309(2), pp.97-113.

Boardman, C.P., Gauci, V. and Beerling, D.J., 2008, December. Wetland Methane Emission Response to Last Glacial Maximum Atmospheric Carbon Dioxide Concentration. AGU Fall Meeting Abstracts, B11F-05.

Calabrese, S., Garcia, A., Wilmoth, J.L., Zhang, X. and Porporato, A., 2021. Critical inundation level for methane emissions from wetlands. Environmental Research Letters, 16, 044038.

Carmichael, M.J., Bernhardt, E.S., Bräuer, S.L. and Smith, W.K., 2014. The role of vegetation in methane flux to the atmosphere: should vegetation be included as a distinct category in the global methane.

Conrad, R., 1989. Control of Methane Production in Terrestrial Ecosystems. In: Andreae, M.O. and Schimel, D.S., Eds., Exchange of Trce Gases between Terrestrial Ecosystems and the Atmosphere, Wiley, Chichester, 39-58

Conflict and Environment Observatory, 2021. Is South Sudan's Sudd wetland at a fork in the road? At: https://ceobs.org/report-is-south-sudans-sudd-wetland-at-a-fork-in-the-road/

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A. and Joosten, H., 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia, 674, 67-89.

Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Marine and Freshwater Research, 65, 934-941.

Davidson, N.C., Fluet-Chouinard, E. and Finlayson, C.M., 2018. Global extent and distribution of wetlands: trends and issues. Marine and Freshwater Research, 69, 620-627.

Dean, J.F., Middelburg, J.J., Röckmann, T., Aerts, R., Blauw, L.G., Egger, M., Jetten, M.S., de Jong, A.E., Meisel, O.H., Rasigraf, O., Slomp, C.P., 2018. Methane feedbacks to the global climate system in a warmer world. Reviews of Geophysics, 56, 207-250.

Deshmukh, C.S., Julius, D., Evans, C.D., Susanto, A.P., Page, S.E., Gauci, V., Laurén, A., Sabiham, S., Agus, F., Asyhari, A., Kurnianto, S., 2020. Impact of forest plantation on methane emissions from tropical peatland. Global Change Biology, 26, 2477-2495.

Etheridge, D.M., Steele, L., Francey, R.J. and Langenfelds, R.L., 1998. Atmospheric methane between 1000 AD and present: Evidence of anthropogenic emissions and climatic variability. Journal of Geophysical Research: Atmospheres, 103, 15979-15993.

Evans, C.D., Renou-Wilson, F. and Strack, M., 2016. The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. Aquatic Sciences, 78, 573-590.

Evans, C.D., Peacock, M., Baird, A.J., Artz, R.R.E., Burden, A., Callaghan, N., Chapman, P.J., Cooper, H.M., Coyle, M., Craig, E. and Cumming, A., 2021. Overriding water table control on managed peatland greenhouse gas emissions. Nature, 593, 548-552.

Fluet-Chouinard, E., Stocker, B.D., Zhang, Z., Malhotra, A. Melton, J.R., Poulter, B., Kaplan, J.O., Goldewijk, K.K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A.M., Davidson, N., Finlayson, M., Lehner, B., Jackson, R.B., McIntyre, P.B., Extensive global wetland loss over the last three centuries. Nature 614: 281-286 https://doi.org/10.1038/s41586-022-05572-6 https://www.nature.com/articles/s41586-022-05572-6

Gauci, V., Matthews, E., Dise, N., Walter, B., Koch, D., Granberg, G. and Vile, M., 2004. Sulfur pollution suppression of the wetland methane source in the 20th and 21st centuries. Proceedings of the National Academy of Sciences, 101, 12583-12587.

Gauci, V., Dise, N.B., Howell, G. and Jenkins, M.E., 2008. Suppression of rice methane emission by sulfate deposition in simulated acid rain. Journal of Geophysical Research: Biogeosciences, 113, JG000501.

Gauci, V., Figueiredo, V., Gedney, N., Pangala, S.R., Stauffer, T., Weedon, G.P., Enrich-Prast, A., 2022. Non-flooded riparian Amazon trees are a regionally significant methane source. Philosophical Transactions of the Royal Society A, 380, 20200446.

Gedney, N., Huntingford, C., Comyn-Platt, E. and Wiltshire, A., 2019. Significant feedbacks of wetland methane release on climate change and the causes of their uncertainty. Environmental Research Letters, 14, 084027.

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., Couwenberg, J., 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nature communications, 11, 1644.

Hemes, K.S., Chamberlain, S.D., Eichelmann, E., Knox, S.H., Baldocchi, D.D., 2018. A biogeochemical compromise: The high methane cost of sequestering

Everglades National Park, Florida, USA.
By Juan Carlos Muñoz Robredo

carbon in restored wetlands. Geophysical Research Letters, 45, 6081-6091.

Hopcroft, P.O., Valdes, P.J., O'Connor, F.M., Kaplan, J.O. and Beerling, D.J., 2017. Understanding the glacial methane cycle. Nature communications, 8, 14383

IPCC, 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Intergovernmental Panel on Climate Change

IPCC, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, forestry and other land use (AFOLU). Intergovernmental Panel on Climate Change.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Intergovernmental Panel on Climate Change

Jackson, R.B., Saunois, M., Bousquet, P., Canadell, J.G., Poulter, B., Stavert, A.R., Bergamaschi, P., Niwa, Y., Segers, A. and Tsuruta, A., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environmental Research Letters, 15(7), p.071002.

Jeffrey, L.C., Maher, D.T., Chiri, E. et al. (2021). Bark-dwelling methanotrophic bacteria decrease methane emissions from trees. Nat Communications, 12, 2127

Kaplan, J.O., 2002. Wetlands at the Last Glacial Maximum: Distribution and methane emissions. Geophysical Research Letters, 29(6), 1079

Koffi, E.N., Bergamaschi, P., Alkama, R. and Cescatti, A., 2020. An observation-constrained assessment of the climate sensitivity and future trajectories of wetland methane emissions. Science advances, 6, eaay4444.

Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.M., Raynaud, D., Stocker, T.F. and Chappellaz, J., 2008. Orbital and millennial-scale features of atmospheric CH4 over the past 800,000 years. Nature, 453, 383-386.

Lunt, M.F., Palmer, P.I., Feng, L., Taylor, C.M., Boesch, H., Parker, R.J., 2019. An increase in methane emissions from tropical Africa between 2010 and 2016 inferred from satellite data. Atmospheric Chemistry and Physics, 19, 14721-14740.

Lynch, J., Cain, M., Pierrehumbert, R. and Allen, M., 2020. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants. Environmental Research Letters, 15, 044023.

Ma, S., Worden, J.R., Bloom, A.A., Zhang, Y., Poulter, B., Cusworth, D.H., Yin, Y., Pandey, S., Maasakkers, J.D., Lu, X., Shen, L., 2021. Satellite constraints on the latitudinal distribution and temperature sensitivity of wetland methane emissions. AGU Advances, 2, e2021AV000408.

Meinshausen, M., Nicholls, Z., 2022. GWP* is a model, not a metric. Environmental Research Letters, 17, 041002.

Muller, M., 2019. Hydropower dams can help mitigate the global warming impact of wetlands. Nature, 566, 315-317.

Nisbet, E.G., Manning, M.R., Dlugokencky, E.J., Fisher, R.E., Lowry, D., Michel, S.E., Myhre, C.L., Platt, S.M., Allen, G., Bousquet, P. and Brownlow, R., 2019. Very strong atmospheric methane growth in the 4 years 2014–2017: Implications for the Paris Agreement. Global Biogeochemical Cycles, 33(3), pp.318-342.

NOAA, 2022. "Increase in atmospheric methane set another record during 2021". News article at: https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021#:~:text=NOAA's%20preliminary%20analysis%20showed%20the,during%202020%20was%2015.3%20ppb.

Pangala, S.R., Moore, S., Hornibrook, E.R. and Gauci, V., 2013. Trees are major conduits for methane egress from tropical forested wetlands. New Phytologist, 197, 524-531.

Pangala, S.R., Enrich-Prast, A., Basso, L.S., Peixoto, R.B., Bastviken, D., Hornibrook, E.R., Gatti, L.V., Marotta, H., Calazans, L.S.B., Sakuragui, C.M., Bastos, W.R., 2017. Large emissions from floodplain trees close the Amazon methane budget. Nature, 552, 230-234.

Peacock, M., Audet, J., Bastviken, D., Futter, M.N., Gauci, V., Grinham, A., Harrison, J.A., Kent, M.S., Kosten, S., Lovelock, C.E., Veraart, A.J., Evans, C.D. 2021a. Global importance of methane emissions from drainage ditches and canals. Environmental Research Letters, 16, 044010.

Peacock, M., Audet, J., Bastviken, D., Cook, S., Evans, C.D., Grinham, A., Holgerson, M.A., Högbom, L., Pickard, A.E., Zieliński, P. and Futter, M.N., 2021b. Small artificial waterbodies are widespread and persistent emitters of methane and carbon dioxide. Global Change Biology, 27, 5109-5123.

Pearce, F., 2022, Will a Nile canal project dry up the Africa's largest wetland? Yale Environment 360, https://e360.yale.edu/features/will-a-nile-canal-project-dry-up-africas-largest-wetland

Pielke Jr, R., Burgess, M.G. and Ritchie, J., 2022. Plausible 2005–2050 emissions scenarios project between

2° C and 3° C of warming by 2100. Environmental Research Letters, 17, 024027.

Raghoebarsing, A.A., Smolders, A.J., Schmid, M.C., Rijpstra, W.I.C., Wolters-Arts, M., Derksen, J., Jetten, M.S., Schouten, S., Sinninghe Damsté, J.S., Lamers, L.P. and Roelofs, J.G., 2005. Methanotrophic symbionts provide carbon for photosynthesis in peat bogs. Nature, 436, 1153-1156.

Reeve, A.S., Siegel, D.I. and Glaser, P.H., 1996. Geochemical controls on peatland pore water from the Hudson Bay Lowland: A multivariate statistical approach. Journal of Hydrology, 181, 285-304.

Ringeval, B., Friedlingstein, P., Koven, C., Ciais, P., de Noblet-Ducoudré, N., Decharme, B. and Cadule, P., 2011. Climate-CH4 feedback from wetlands and its interaction with the climate-CO2 feedback. Biogeosciences, 8, 2137-2157.

Rosentreter, J.A., Borges, A.V., Deemer, B.R., Holgerson, M.A., Liu, S., Song, C., Melack, J., Raymond, P.A., Duarte, C.M., Allen, G.H. and Olefeldt, D., 2021. Half of global methane emissions come from highly variable aquatic ecosystem sources. Nature Geoscience, 14, 225-230.

Ruddiman, W. (2003) The anthropogenic greenhouse era began thousands of years ago. Climate Change. 61, 261-293

Saunois, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K., Ciais, P., 2020. The global methane budget 2000–2017. Earth system science data, 12(3), pp.1561-1623.

Shindell, D.T., Walter, B.P., Faluvegi, G., 2004. Impacts of climate change on methane emissions from wetlands. Geophysical Research Letters, 31, GL021009.

Singarayer, J.S., Valdes, P.J., Friedlingstein, P., Nelson, S. and Beerling, D.J., 2011. Late Holocene methane rise caused by orbitally controlled increase in tropical sources. Nature, 470(7332), pp.82-85.

UNFCCC, 2021. Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to 13 November 2021. United Nations Framework Convention on Climate Change.

Wetlands International, 2021. Wetlands International response to the Global Methane Pledge. At: https://www.wetlands.org/cop26/.

Zhang, Z., Zimmermann, N.E., Stenke, A., Li, X., Hodson, E.L., Zhu, G., Huang, C. and Poulter, B., 2017. Emerging role of wetland methane emissions in driving 21st century climate change. Proceedings of the National Academy of Sciences, 114, 9647-9652.

Peatland, Bleaklow Ridge, England. By Peter Blakely

Aerial view of Danube Delta, Romania.
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