CellPress
OPEN ACCESS

One Earth

Primer

Methane and nitrous oxide emissions complicate the climate benefits of teal and blue carbon wetlands

Martino E. Malerba,[1,*] Daniel A. Friess,[2,3] Mike Peacock,[4,5] Alistair Grinham,[6] Pierre Taillardat,[7] Judith A. Rosentreter,[8] Jackie Webb,[9] Naima Iram,[10,11] Alia N. Al-Haj,[12] and Peter I. Macreadie[1]

[1]Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood Campus, Burwood, VIC 3125, Australia
[2]Department of Geography, National University of Singapore, 1 Arts Link, Singapore 117570, Singapore
[3]Centre for Nature-based Climate Solutions, National University of Singapore, 16 Science Drive 4, Singapore 117558, Singapore
[4]Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Liverpool L69 3GP, UK
[5]Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden
[6]School of Civil Engineering, The University of Queensland, St Lucia, QLD 4072, Australia
[7]NUS Environmental Research Institute, National University of Singapore, Singapore 117411, Singapore
[8]Centre for Coastal Biogeochemistry, Faculty of Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia
[9]Centre for Regional and Rural Futures (CeRRF) Faculty of Science, Engineering and Built Environment Deakin University, Research Station Road, Griffith, NSW 2680, Australia
[10]Australian Rivers Institute, Griffith University, Brisbane, QLD, Australia
[11]Coastal and Marine Research Centre, Griffith University, Brisbane, QLD, Australia
[12]Department of Earth & Environment, Boston University, Boston, MA 02215, USA
*Correspondence: m.malerba@deakin.edu.au
https://doi.org/10.1016/j.oneear.2022.11.003

SUMMARY

Blue (coastal wetlands) and teal (inland wetlands) carbon ecosystems are long-term carbon sinks and are regarded as essential natural climate solutions. Yet, the same biogeochemical conditions favoring high carbon storage also promote the production of two potent greenhouse gases (GHGs)—methane and nitrous oxide—which can reduce the climate change mitigation potential of wetlands. Complex processes regulate the production and consumption of the two GHGs, complicating our understanding of wetlands' net warming or cooling effects on the climate. This primer offers an overview of the current knowledge of wetland GHG dynamics and discusses management actions available to stakeholders to maximize blue and teal carbon potential. Improving our monitoring of these ecosystems will yield more realistic estimates and avoid misrepresenting their true climate change mitigation potential. This is vital for establishing sustainable financial mechanisms (through carbon credits) to manage these ecosystems at scale.

WETLANDS ARE CARBON SINKS AND GREENHOUSE GAS SOURCES

Vegetated coastal and inland wetlands are essential components of global carbon and nitrogen cycles. They can take up atmospheric CO_2 and preserve it in their sediments at high rates and densities for centuries and millennia. The long-term storage of organic and inorganic carbon in coastal wetlands (such as mangroves, tidal marshes, and seagrasses) is referred to as "blue carbon," whereas carbon in inland wetlands (such as ponds, marshes, and swamps) is called "teal carbon." Protecting and restoring wetlands is an increasingly popular natural climate solution to mitigate climate change while supporting other sustainable development goals, such as contributing to cleaner water, coastal protection, sustainable livelihoods, and higher biodiversity.

To mitigate climate change, wetlands need to be net carbon sinks at the whole ecosystem scale. However, this assessment is complicated because wetlands emit greenhouse gases (GHGs) into the atmosphere in the forms of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and these fluxes are highly uncertain. Various factors influence GHG fluxes in wetlands. For example, low dissolved oxygen concentrations in sediments can boost methane production, or nitrogen pollution can generate N_2O, a greenhouse gas nearly 300 times more potent than CO_2. These processes are highly variable over spatial and temporal scales and challenging to predict but can have profound implications on wetlands' warming and cooling effects on the atmosphere.

Despite the growing enthusiasm for blue carbon and teal carbon, GHG emissions from wetlands could reduce their true potential as natural climate solutions, introducing challenges to their conservation. By reducing the uncertainties of wetlands' cooling and warming effects on the atmosphere, it will be possible to calculate their climate change mitigation potential more accurately. This is particularly important with increasing interest in developing financial mechanisms (through carbon credits) to reward the protection and restoration of wetlands as

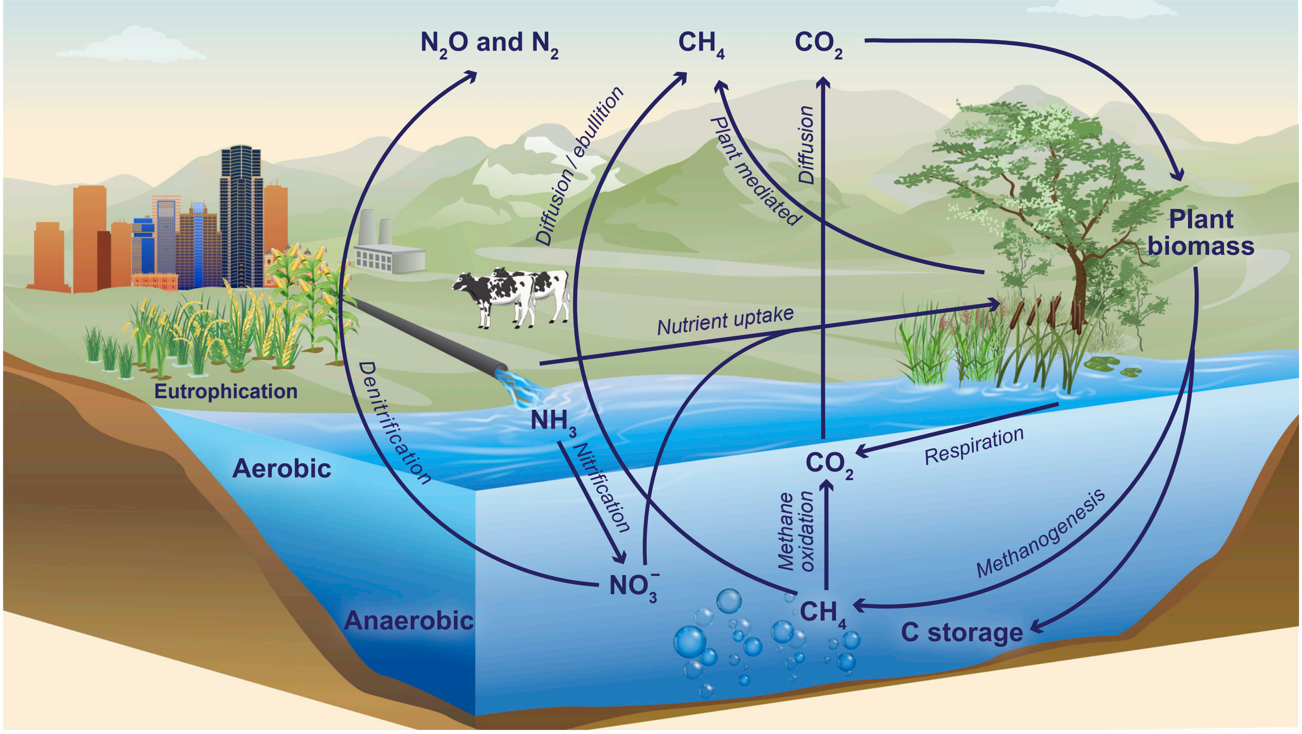

Figure 1. The effects of the carbon and nitrogen cycles on GHG emissions (CH_4, CO_2, and N_2O) and carbon stocks of wetlands
Stores are indicated in regular font, and rates are italicized. Shades of blue show the gradient between aerobic and anaerobic conditions in the wetland.

"Nationally Determined Contributions" under the Paris Agreement or in the voluntary carbon market for private companies to offset their carbon footprint.

In this primer, we discuss the following: (1) the drivers of the CH_4 and N_2O in wetlands, (2) how management actions can affect carbon and nitrogen fluxes, (3) the benefits of preserving and restoring wetlands for climate change, (4) the sources of uncertainty about the role of wetlands in climate change mitigation, and (5) policy actions for cost-effective management of wetlands as a natural climate solution.

DRIVERS OF CH_4 AND N_2O EMISSIONS IN WETLANDS

In blue and teal carbon ecosystems, GHG fluxes are closely linked to plant productivity. Plants assimilate atmospheric CO_2 into their biomass, which drives GHG emissions back to the atmosphere when the organic matter eventually decomposes in waterlogged conditions. However, only a fraction of the total organic matter will decay and turn into CO_2 or CH_4, while the rest will be exported to the ocean or preserved in the sediments, increasing the soil carbon stock. The partitioning between carbon storage and GHG emissions is key to whether a wetland acts to cool or warm the atmosphere and depends on several environmental factors, including wetland type, salinity, hydrological conditions, dissolved oxygen, nutrients, and others (Figure 1).

Teal carbon ecosystems generally emit 10–100 times higher CH_4 and N_2O fluxes than blue carbon ecosystems to preserve the same amount of carbon in their soil. The main driver of these differences is salinity, which causes greater osmotic stress and reduced efficiency of microbial communities involved in CH_4 and N_2O production in coastal environments. Moreover, coastal sediments are rich in sulfate-reducing bacteria that outcompete methane-producing microbes. As a result, methane emissions are usually lower in coastal ecosystems than in freshwater wetlands.

The type of vegetation is another critical factor driving CH_4 and N_2O emissions. Some plants produce less methane than others because they allocate more oxygen to the rhizosphere, inhibiting CH_4 production (methanogenesis). While there are exceptions, trends in N_2O are often the opposite of CH_4, with plants producing the lowest CH_4 also creating the conditions for the highest N_2O fluxes (Figure 1). Another essential role of wetland vegetation is to enable plant-mediated methane fluxes, an emission pathway where methane travels from sediments to the atmosphere inside plant tissues. This pathway often dominates total methane fluxes in vegetated wetlands (Figure 1).

Dissolved oxygen in the sediments is another essential driver, particularly for methane emissions. The concentration of dissolved oxygen differentiates aerobic and anaerobic sediments in wetlands. Microbe-mediated methanogenesis occurs in oxygen-free (anoxic) sediments of coastal and inland wetlands. Hence, increasing dissolved oxygen decreases anaerobic respiration and methanogenesis by reducing the availability of anaerobic sediments (Figure 1).

Nutrient concentrations in wetlands affect CH_4 and N_2O emissions by fertilizing plants, increasing the influx of organic carbon in the sediments, and promoting faster decomposition. Also, excess nutrients convert reactive nitrogen into N_2O gas through denitrification (e.g., nitrate, nitrite) and nitrification (e.g., ammonium, ammonia). Finally, eutrophication increases the production and decomposition of organic matter, reducing dissolved oxygen in the water column and increasing CH_4 production (Figure 1).

UNDERSTANDING THE ROLE OF WETLANDS IN CLIMATE CHANGE

Blue and teal carbon ecosystems release and absorb GHG simultaneously, making their role in mitigating climate change complex to quantify. Production and consumption of CH_4 and N_2O depend on climatic, geomorphologic, physical, and biogeochemical factors. However, these factors interact in complex ways to regulate carbon dynamics. For example, there are different possible transport pathways of CH_4 and N_2O to reach the atmosphere—diffusion, methane bubbles (ebullition), and plant-mediated fluxes (Figure 1)—all of which interact differently with environmental parameters. These factors depend on complex microbial interactions that can rapidly turn systems from sources to sinks and vice versa.

Understanding how to manage wetlands to maximize carbon removal while reducing CH_4 and N_2O emissions is challenging, and this uncertainty has implications for wetland conservation and restoration. Moreover, many wetlands alternate between dry and wet phases depending on water table height (inland systems) and tidal dynamics (coastal systems). The frequency and duration of wet-dry cycles can change substantially over daily, seasonal, or inter-annual scales, with important implications for CH_4 and N_2O dynamics, further complicating the assessment of their warming and cooling effects on the climate.

Another source of uncertainty is that CO_2, CH_4, and N_2O have different heat-trapping potentials, and comparing CH_4 and N_2O to radiative forcing effects relative to CO_2 is non-trivial. Several methods in the literature quantify the heating potential of gas in the atmosphere, with no clear consensus on the most suitable approach. One widespread method is the Global Warming Potential (GWP) to convert CH_4 and N_2O into CO_2-equivalent (CO_2-e) units by simulating an emission pulse over time. Another method is the Sustained-Flux Global Warming Potential (SGWP) to convert CH_4 and N_2O into CO_2-e by assuming a gradual release (non-pulse) over time. The choice between GWP and SGWP has substantial implications. For example, the latest Intergovernmental Panel on Climate Change (IPCC) report uses the GWP metric and assumes that 1 ton of CH_4 or N_2O over 100 years has the same effects as 27.9 or 273 tons of CO_2, respectively. Instead, using the SGWP would yield 40% higher CO_2-e values for CH_4 but similar values for N_2O.

Regardless of the choice of metric to calculate CO_2-e units (e.g., GWP or SGWP), another complication is that GHGs differ in how long they can emit heat in the atmosphere (“lifetime”). As a result, calculating CO_2-eq units for GHGs with different lifetimes means the net effect of a wetland on the atmosphere can change over time. For example, methane generates a significant amount of warming in the atmosphere but only for a short period (12.4 years), whereas CO_2 generates less heat per unit mass but can last in the atmosphere (or in the soil) for much longer (300–1,000 years, and up to geological timescales). Specifically, the SGWP of 1 ton of methane equals 96 tons of CO_2 over 20 years and decreases to 45 tons of CO_2 over 100 years and to 1 ton of CO_2 over 12,905 years. Therefore, the arbitrary time horizon set in the calculations can significantly affect the outcome. For example, a wetland may qualify as net warming over a short time horizon (when the warming effect of methane emissions is more significant than the cooling effect from carbon burial) and switch to net cooling over a more extended period (as the warming potential of methane in the atmosphere decreases). The time when the net effect of a wetland turns from net warming (positive radiating forcing) to net cooling (negative radiating forcing) is called the “switchover time.”

Finally, another challenge is to develop suitable methods for comparing results on CH_4 and N_2O emissions among studies. Currently, there is no consensus on a “gold standard” for measuring CH_4 or N_2O, with studies using inconsistent and sometimes incompatible statistics. The lack of empirical data combined with incompatible statistical analysis contributes to higher uncertainties. Establishing an accepted methodology would facilitate the development of a global database and improve our confidence in GHG fluxes in wetlands.

MANAGING WETLANDS TO MAXIMIZE CLIMATE CHANGE MITIGATION

Natural wetlands are best left undisturbed to conserve long-term carbon storage and maintain a net cooling effect on the atmosphere. Conversely, disturbed wetlands require active management to lessen their impacts on climate change and improve other essential benefits, including biodiversity, cultural significance, flood protection, and drought resilience. Typical management actions for controlling GHG emissions are restoring natural hydrology, revegetation, and reducing eutrophication (Figure 2).

The hydrological restoration of a wetland is a promising management intervention to revive natural carbon sequestration rates and reduce GHG emissions. Restoring tidal flows of areas that have been diked, impounded, drained, or tidally restricted boosts carbon sequestration from blue carbon ecosystems. Similarly, artificially flooding dried areas can help increase the extent of teal carbon ecosystems and preserve their old carbon stocks by stimulating vegetation growth and avoiding the decomposition of organic carbon stored in anoxic sediments (Figure 2). Alternatively, slowing water flow and increasing water residence time in managed teal wetlands can further increase carbon sequestration by promoting emergent vegetation and sedimentation, which adds organic carbon and soil to sediments. Yet, overly reducing water flow may reduce dissolved oxygen, increasing the likelihood of anoxic conditions and higher methane production.

Promoting vegetation and reducing eutrophication lower methane production in the sediments by increasing dissolved oxygen in the water, which diminishes methanogenesis (Figure 2). Emergent and floating plants oxygenate wetlands through photosynthesis. Yet, excessive plant density (in combination with high nutrients) can also enhance CH_4 emissions by releasing labile methanogenic substrates into the sediments and providing a plant-mediated pathway for CH_4 to be released directly into the atmosphere. To dilute the effects of excessive vegetation contributing to CH_4, teal waterbodies could be

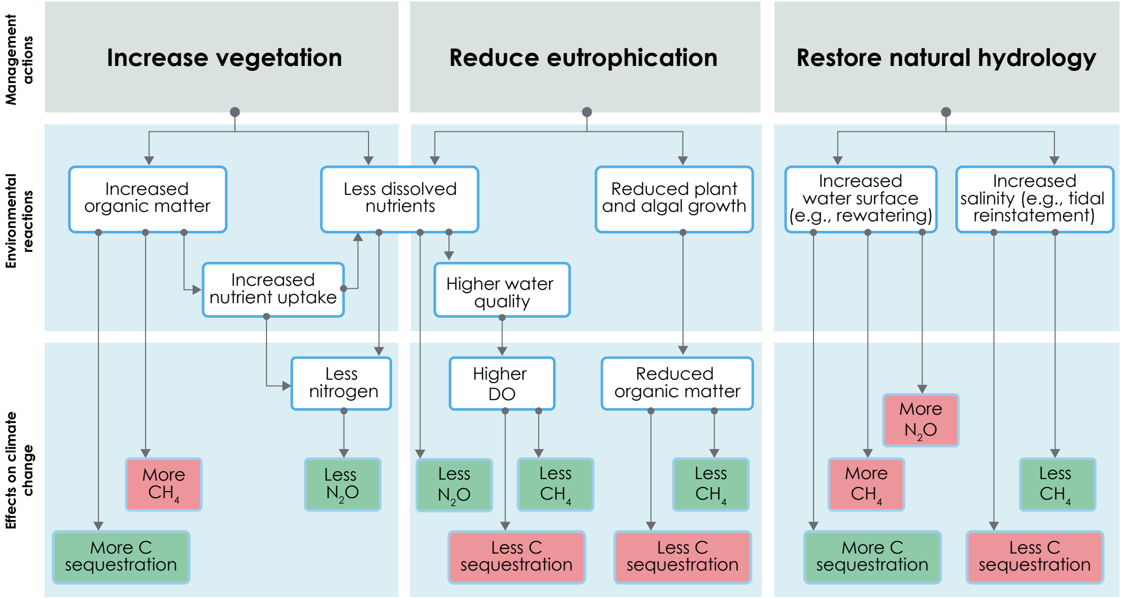

Figure 2. Main management actions available to stakeholders, their reactions to environmental properties, and consequential effects on climate change

Cooling effects are in green, and warming effects are in red.

maintained at higher water levels to regulate temperature, reduce ebullition events, and increase the consumption of dissolved CH_4 in the water column via methane oxidation.

Wetlands with established vegetation can absorb CO_2 (and sometimes even N_2O) from the atmosphere to offset some (or potentially all) CH_4 emissions. Unlike CH_4, anaerobic conditions in the sediments reduce N_2O production (by coupled nitrification-denitrification) and promote N_2O consumption (by complete denitrification), turning wetlands into N_2O sinks. However, N_2O may be released back into the atmosphere, for example, when sediments dry out or receive high nitrogen loading (Figure 2).

Another way to maximize the carbon benefits of wetlands is to improve water quality by reducing dissolved nitrogen and phosphorous inputs and increasing dissolved oxygen, thereby reducing wetland CH_4 and N_2O emissions (Figure 2). Protecting wetlands from anthropogenic nutrient inputs is a viable way to lower CH_4 and N_2O emissions. In agricultural waterbodies, installing fences and water throughs to exclude livestock from accessing wetlands are simple management interventions that can reduce GHG emissions by lowering nutrient input from animal waste, promoting natural revegetation for additional water quality benefits, and preventing soil compaction from decreasing oxygen in the sediments (Figure 2).

PRIORITIES FOR HEALTHY WETLANDS

Despite the uncertainties associated with the overall cooling effect of wetlands, ensuring effective and long-lasting conservation of blue and teal carbon wetlands should be a priority to meet climate change mitigation goals. Most undisturbed wetlands have cooling effects on the atmosphere (cumulative negative forcing) because their organic carbon burial rates are sustained over decades and centuries to exceed their GHG emissions. Other than mitigating climate change, healthy wetlands offer essential ecosystem services, such as water security, biodiversity benefits, and flood mitigation. Their continued preservation will also protect the cultural and recreational significance as “wild and natural” areas in an increasingly modified world. To this end, urgent management priorities include (1) protecting undisturbed wetlands, (2) restoring degraded wetlands, and (3) advancing our understanding of their carbon dynamics (Figure 3).

The most urgent management action is to ensure that undisturbed wetlands remain protected. Avoiding human disturbances is the most cost-effective solution to maintain carbon sequestration rates and preserve the carbon stocks accumulated in wetland sediments over centuries and millennia (Figure 3). Effective communication to raise awareness on the roles of wetlands in the environment will play an essential role in involving the public to support investments in management actions to protect the conditions of these systems (Figure 3).

Another priority is to restore degraded wetlands to reduce their contributions to climate change (Figure 3). Degraded wetlands have higher CH_4 and N_2O fluxes, lower carbon sequestration rates, and net warming effects on the atmosphere. Restoring degraded teal and blue carbon ecosystems can reduce their emissions, improve their carbon sequestration, and eventually return these systems to have a cooling effect on the climate. Typically, blue carbon ecosystems may return to their net cooling effects a decade after restoration, whereas teal carbon ecosystems may take longer (up to several centuries).

Reducing eutrophication by protecting wetlands from anthropogenic nutrient inputs is a viable way to reduce CH_4 emissions (Figure 3). Restoring natural hydrology and promoting vegetation will help reduce nutrient loads and improve wetland conditions. However, some wetlands in urban and agricultural areas are

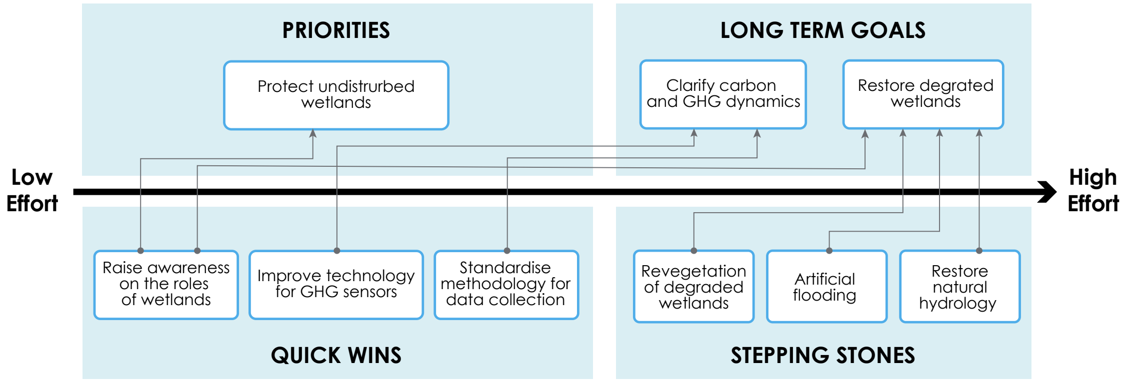

Figure 3. Prioritizing management actions for healthier wetlands
Activities are ranked based on implementation efforts (estimated by the authors) and classified into four broad categories. Arrows link complementary activities, whereby local actions can pave the way for broader benefits.

specifically designed to trap and bury nutrients in the sediments, likely increasing their CH_4 production. When reducing nutrients upstream is an unfeasible option, higher CH_4 emission may be a price worth paying for reducing downstream eutrophication in systems.

Investing in more research to clarify CH_4 and N_2O dynamics in wetlands is crucial (Figure 3). As discussed, wetlands can emit these potent greenhouse gases while simultaneously acting as significant carbon sinks. There is another complication: what proportion of these emissions can be directly attributed to wetlands? For example, most N_2O emissions from wetlands originate from anthropogenic nitrogen inputs (e.g., fertilizers); therefore, these emissions would still occur elsewhere in the hydrological network if the wetlands were absent. Thus, wetlands should not be "blamed" for emitting N_2O when the nutrient input comes from terrestrial sources. By contrast, CH_4 emissions are a specific by-product of the decomposition of organic matter in the anoxic sediments, and these emissions would not exist without a wetland. Nonetheless, the same anoxic sediments promoting methanogenesis are also essential for carbon sequestration, which can typically offset emissions in healthy wetlands. Hence, clarifying the fluxes in the carbon cycle can prevent missing or double counting the effects of wetlands on the atmosphere.

A better understanding of CH_4 and N_2O emissions and carbon sink dynamics requires improving the quality of our datasets. First, we need to ensure that the data collected by scientists can be compared and compiled in global datasets. This requires reaching a consensus on techniques that provide compatible results for measuring CH_4 and N_2O with high accuracy and precision (Figure 3). Second, we need to improve the technology for collecting data from the field. Wetland emissions are highly variable in time and space, and capturing the appropriate temporal and spatial resolution is difficult. One limitation is that CH_4 and N_2O sensors have higher costs and lower accuracies than CO_2 sensors. There is increasing urgency to develop low-cost, commercial sensors for scientists, technicians, or private citizens to monitor emissions in the environment (Figure 3). Such approaches are particularly needed for emissions in aquatic systems, which are highly episodic and represent the largest source of uncertainty in global budgets for N_2O and CH_4. Deciphering the magnitudes and origins of these emissions worldwide is the first step to reducing them with effective climate policies, along with generating other co-benefits.

RECOMMENDED READING

Goldstein, A., Turner, W.R., Spawn, S.A., Anderson-Teixeira, K.J., Cook-Patton, S., Fargione, J., Gibbs, H.K., Griscom, B., Hewson, J.H., Howard, J.F., et al. (2020). Protecting irrecoverable carbon in Earth's ecosystems. Nat. Clim. Change *10*, 287–295.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., et al. (2017). Natural climate solutions. Proc. Natl. Acad. Sci. USA *114*, 11645–11650.

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., and Couwenberg, J. (2020). Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat. Commun. *11*, 1–5.

Iram, N., Maher, D.T., Lovelock, C.E., Baker, T., Cadier, C., and Adame, M.F. (2022). Climate change mitigation and improvement of water quality from the restoration of a subtropical coastal wetland. Ecol. Appl. *32*, e2620.

Kroeger, K.D., Crooks, S., Moseman-Valtierra, S., and Tang, J. (2017). Restoring tides to reduce methane emissions in impounded wetlands: a new and potent Blue Carbon climate change intervention. Sci. Rep. *7*, 1–12.

Malerba, M.E., Lindenmayer, D.B., Scheele, B.C., Waryszak, P., Yilmaz, I.N., Schuster, L., and Macreadie, P.I. (2022). Fencing farm dams to exclude livestock halves methane emissions and improves water quality. Glob. Chang. Biol. *28*, 4701–4712.

Neubauer, S.C., and Megonigal, J.P. (2015). Moving beyond global warming potentials to quantify the climatic role of ecosystems. Ecosystems *18*, 1000–1013.

Prairie, Y.T., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J., Del Giorgio, P., DelSontro, T., Guérin, F., Harby, A., et al. (2018). Greenhouse gas emissions from freshwater reservoirs: what does the atmosphere see? Ecosystems *21*, 1058–1071.

Rosentreter, J.A., Al-Haj, A.N., Fulweiler, R.W., and Williamson, P. (2021a). Methane and nitrous oxide emissions complicate coastal blue carbon assessments. Global Biogeochem. Cycles *35*.

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., et al. (2021b). Half of global methane emissions come from highly variable aquatic ecosystem sources. Nat. Geosci. *14*, 225–230.

Shiau, Y.-J., and Chiu, C.-Y. (2020). Biogeochemical processes of C and N in the soil of mangrove forest ecosystems. Forests *11*, 492.

Taillardat, P., Thompson, B.S., Garneau, M., Trottier, K., and Friess, D.A. (2020). Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus *10*, 20190129.

Valach, A.C., Kasak, K., Hemes, K.S., Anthony, T.L., Dronova, I., Taddeo, S., Silver, W.L., Szutu, D., Verfaillie, J., and Baldocchi, D.D. (2021).

Productive wetlands restored for carbon sequestration quickly become net CO_2 sinks with site-level factors driving uptake variability. PLoS One *16*, e0248398.

Webb, J.R., Hayes, N.M., Simpson, G.L., Leavitt, P.R., Baulch, H.M., and Finlay, K. (2019a). Widespread nitrous oxide undersaturation in farm waterbodies creates an unexpected greenhouse gas sink. Proc. Natl. Acad. Sci. USA *116*, 9814–9819.

Webb, J.R., Leavitt, P.R., Simpson, G.L., Baulch, H.M., Haig, H.A., Hodder, K.R., and Finlay, K. (2019b). Regulation of carbon dioxide and methane in small agricultural reservoirs: optimizing potential for greenhouse gas uptake. Biogeosciences *16*, 4211–4227.

Williamson, P., and Gattuso, J.-P. (2022). Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. Front. Clim. *4*.

Zheng, Y., Wu, S., Xiao, S., Yu, K., Fang, X., Xia, L., Wang, J., Liu, S., Freeman, C., and Zou, J. (2022). Global methane and nitrous oxide emissions from inland waters and estuaries. Glob. Chang. Biol. *28*, 4713–4725.

Zou, J., Ziegler, A.D., Chen, D., McNicol, G., Ciais, P., Jiang, X., Zheng, C., Wu, J., Wu, J., Lin, Z., et al. (2022). Rewetting global wetlands effectively reduces major greenhouse gas emissions. Nat. Geosci. *15*, 627–632.