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How to Achieve Net Greenhouse Gas Reductions Through Wetland Restoration?

Summary

Wetlands play an important role in mitigating climate change: vegetation and sediment in wetlands can absorb carbon dioxide (CO_2) from the atmosphere, which makes wetland restoration a compelling approach to mitigate climate change. At the same time, research shows that under some conditions wetland soils produce another potent greenhouse gas, methane. As a result, wetland restoration is sometimes seen as controversial in mitigating climate change. However, careful analysis shows that concerns about methane should not serve as an argument against wetland restoration and protection.

A significant body of scientific research has characterized the mechanisms that lead to reduced greenhouse gas emissions from wetlands. Results show that oxygen levels, soil temperature, and vegetation coverage are key factors affecting wetland CO_2 and methane emissions. In addition to the literature, on-the-ground wetland restoration projects have demonstrated that wetland restoration is an effective measure to mitigate greenhouse gas emissions in the long term, even with the trade-offs between methane and CO_2 emissions.

Wetland restoration projects in the Sacramento-San Joaquin Delta, California are good examples of greenhouse gas mitigation in wetlands. Through land-use changes, greenhouse gas monitoring, and carbon offset credit acquisition, these projects demonstrate a pathway to mitigate greenhouse gas emissions while also supporting biodiversity, delivering economic benefits, and reversing ground subsidence. Some best practices from these projects include (1) converting agricultural lands to a rice-wetland mosaic, (2) quantifying baseline greenhouse gas emissions through model estimation and eddy covariance techniques, and (3) Incorporating more wetland restoration projects into the carbon market.

The Role of Wetlands in Mitigating Climate Change

What are Wetlands?

Wetlands are areas where water is the primary factor controlling the environment and associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by water.[1] There are many types of wetlands in the United States (U.S.), ranging from inland nontidal marshes to coastal tidal mangrove swamps, which possess different characteristics in soils, climate, hydrology, and other factors. Providing habitat for thousands of species of aquatic and terrestrial plants and animals, wetlands carry multiple ecological values, such as flood protection, shoreline erosion prevention, water quality improvement, and natural products (such as fish and plants).[2] Wetlands also serve as aesthetic and recreational spaces that provide social and cultural benefits for people.[3]

The Role of Wetlands in Mitigating Climate Change

Wetland and Carbon Dioxide Mitigation

Wetlands are not only important for the environment and species, but they also play an important role in mitigating climate change; vegetation in wetlands can absorb carbon dioxide from the atmosphere and store it, making them "carbon sinks" that directly mitigate climate change.[4] For example, a report from the U.S. Global Change Research Program suggests that nontidal[5] freshwater wetlands in North America are a carbon dioxide (CO_2) sink that absorbs about 123 million metric tons of carbon per year, and store about 161 billion metric tons of carbon in their soil and vegetation, representing approximately 36% of global wetland carbon stock.[6] As for tidal wetlands,[7] it was estimated that the top one meter of tidal wetland soils and estuarine sediments in North America contains 1.9 ± 1.0 billion metric tons of carbon, while tidal wetlands intake 27 ± 13 million metric tons of carbon from the atmosphere per year.[8] Therefore, the protection and restoration of wetlands are crucial to preserving their net cooling effect on the atmosphere.

Wetland and Methane Emissions

Even though wetlands are usually net carbon sinks,[9] their soils can serve as the source of another greenhouse gas to the atmosphere,[10] methane, which has more than 80 times the global warming

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[1] The Ramsar Convention, n.d.

[2] Long et al., 2022

[3] California Water Quality Monitoring Council, 2016

[4] Lovelock et al., 2023

[5] Nontidal wetlands are inland, freshwater areas not subject to tidal influence. They are typically areas where the water table is at or near the surface, or the land is covered by shallow water. (Maryland Department of the Environment, n.d.)

[6] Kolka et al., 2018, p. 508

[7] Tidal wetlands are flat, vegetated areas that are subject to regular flooding by the tides. These types of wetlands feature different salinity levels and fluctuating water levels. (Connecticut Department of Energy and Environmental Protection, 2018; United States Environmental Protection Agency, 2023b)

[8] Windham-Myers, Cai, et al., 2018, p. 597

[9] Salimi et al., 2021, p. 3

[10] Kolka et al., 2018, p. 512

impact of carbon dioxide over a 20-year timeframe.[11] This is because wetlands tend to have relatively high water levels and low oxygen levels in their soils, which causes the microbes that live in the soil to decompose organic matter in the absence of oxygen and produce methane.[12] Globally, wetlands are the largest natural source of methane emissions;[13] it is estimated that the average amount of methane emissions from wetlands ranges from 102 to 200 million metric tons over the period of 2008 – 2017, which is about one-quarter of global methane emissions.[14] In the future, if climate change continues unabated and global temperature keeps rising, methane emissions from wetlands will likely increase, potentially undermining the climate change mitigation potential of wetlands.[15]

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[11] Zhu et al., 2023, p. 3
[12] Wilmoth et al., 2021
[13] Zhang et al., 2017
[14] United Nations Environment Programme & Climate and Clean Air Coalition, 2021, p. 37
[15] Bao et al., 2023

Current Research About Managing Wetland Greenhouse Gas Emissions

Factors that Affect Wetland Greenhouse Gas Flux

There are three common factors that affect the greenhouse gas emissions from wetlands: oxygen level (which is affected by soil water saturation level), soil temperature, and wetland vegetation coverage.[16] The typical impacts of these factors on wetland greenhouse gas emissions are summarized in Table 1. Other potential factors include precipitation, hydrology, land topology, wetland soil type (mineral soil or peatland), wetland location (terrestrial or coastal), wetland size, and land use.[17]

Table 1. Factors that affect wetland greenhouse gas emissions and their typical respective impact.[18]

Factors	Oxygen Level (linked to water saturation level)		Soil Temperature		Vegetation Coverage	
Change	Increase (lower water saturation level)	Decrease (higher water saturation level)	Increase	Decrease	Increase	Decrease
CO_2	Increase	Decrease	Increase	Decrease	Decrease	Increase
Methane	Decrease	Increase	Increase	Decrease	Increase	Decrease

However, there are still uncertainties surrounding greenhouse gas emissions from wetlands.[19] Multiple factors can affect greenhouse gas emissions from wetlands simultaneously and it is difficult to determine the impact of each individual factor. For example, even for those common factors in Table 1, their impacts on wetland greenhouse gas emissions also depend on the amount of organic matter in the soil, vegetation type, and changes in hydrology and precipitation due to climate change.[20] More modeling and field research is necessary to further understand the mechanisms behind wetland greenhouse gas emissions and to inform decision-making.[21]

Besides oxygen, temperature, and vegetation, it should be noted that aqueous sulfate concentrations can reduce wetland methane production by modulating microbial processes. In anaerobic conditions, sulfate-reducing microbes competitively consume sulfate, limiting carbon

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[16] Bansal et al., 2023

[17] Bansal et al., 2023; Kolka et al., 2018

[18] Bansal et al., 2023; Kolka et al., 2018; Swails et al., 2022; Temmink et al., 2022

[19] United Nations Environment Programme & Climate and Clean Air Coalition, 2021, p. 37

[20] Koh et al., 2009

[21] Zhang et al., 2023

compounds essential for methane production.[22] Notably, observations in sulfate-rich wetlands like Suisun Marsh exhibit comparable carbon storage to wetlands in the Sacramento-San Joaquin River Delta in California but emit less methane.[23]

How to Better Utilize Wetland Restoration to Mitigate Climate Change

A large body of scientific research shows that the restoration of wetlands can effectively mitigate climate change. For example, a research project on California's San Francisco Bay Delta concluded that the restoration of coastal wetlands can make wetlands net carbon sinks and immediately contribute to atmospheric carbon removal.[24] Even though the restoration of nontidal wetlands will increase methane emissions, which will offset carbon removal from the atmosphere for 2 to 8 decades,[25] it can still achieve net carbon sequestration in the long term.[26] Another research finding shows that greenhouse gas emissions from wetlands are kept to a minimum when the water table[27] is near the wetland surface, whereas flooded or drained wetlands will have much higher greenhouse gas emissions. This points to the inherent connection between land management practices and the release of methane and CO_2 and suggests that these can be balanced to achieve net greenhouse gas emission reductions – for example, increasing the storage of atmospheric CO_2 to compensate for increased methane emissions.[28]

To some degree, there is an unavoidable trade-off between methane and CO_2 emissions for rewetting drained wetlands; methane emission is an intrinsic feature of wetlands, and the restoration of these systems may result in a short-term peak of methane emissions. However, concerns about methane are not an argument against wetland restoration, but rather an argument in favor of the best management techniques to reduce wetland methane emissions while creating conditions that are good for CO_2 sequestration. Examples of such techniques include:

- raising water levels in drained wetlands to a certain depth (10 - 30 centimeters)[29]
- cultivating decay-resistant, peat-forming species to reduce materials that enhance methane production[30]
- removing artificially high amounts of nutrients during the early stages of restoration[31]
- avoiding prolonged summer inundation[32]
- flooding regularly with sulfate-containing water[33]

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[22] He et al., 2015
[23] Knox et al., 2017
[24] Arias-Ortiz et al., 2021
[25] Arias-Ortiz et al., 2021
[26] Temmink et al., 2022
[27] The water table is the boundary between the unsaturated zone and the saturated zone underground. Below the water table, groundwater fills any spaces between sediments and within rock (National Geographic Society, 2023).
[28] Zou et al., 2022
[29] C. D. Evans et al., 2021
[30] Chimner et al., 2019
[31] C. Evans & Gauci, 2023
[32] C. Evans et al., 2016
[33] Vile et al., 2003

- water management practices that maintain sulfate concentrations[34] at levels that can inhibit methanogenesis.[35]
- top-soil removal[36]
- removing fresh biomass before restoration[37]

Finally, addressing climate change is necessary to support the role of wetlands as a mitigation tool; wetland systems are increasingly at risk of becoming net sources of greenhouse gas emissions as climate impacts like extreme heat and drought escalate.[38] Therefore, climate policies such as energy decarbonization, industrial decarbonization, and enhancing low-carbon transportation should be implemented in tandem with nature-based climate solutions to prevent massive carbon release from wetlands.

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[34] Sulfate's role involves restricting methanogenic pathways through metabolic competition with sulfate reducers or direct inhibition by resulting sulfides (Poffenbarger et al., 2011). The Sacramento-San Joaquin River Delta ("Delta") is a good example. Although sulfate naturally occurs in diverted Delta river water, concentrations decrease with time in the anoxic organic soils (Deverel et al., 1986). Studies at Delta's West Pond wetland reveal increasing methane emissions along hydrologic flow paths, indicating a residence time effect (Windham-Myers, Bergamaschi, et al., 2018). Similarly, methane production was lower near the wetland inlet versus transitional/interior zones (He et al., 2015). Greater sulfate-reducing bacterial abundance also occurred near the inlet (He et al., 2015), aligning with the effect of sulfate availability. These spatial patterns suggest water residence time can mediate sulfate concentrations which can reduce methane fluxes. Strategic water management practices that reduce residence times to maintain aqueous sulfate could help reduce methane production from restored Delta wetlands while sustaining carbon sequestration.

[35] Methanogenesis is an anaerobic respiration that generates methane as the final product of metabolism (Lyu et al., 2018).

[36] Huth et al., 2020

[37] Convention on Wetlands, 2021

[38] Bao et al., 2023

Case Study: Wetland Management in Sacramento-San Joaquin Delta, California

Formed by the Sacramento and San Joaquin rivers, the Sacramento-San Joaquin River Delta ("Delta") is an expansive inland river delta in Northern California. The total area of the Delta is about 1,000 square miles.[39] It plays a vital role in California's water conveyance system and in supporting the state's substantial agricultural production and provides critical habitat for a wide array of plants and animals, especially birds.

Unfortunately, the Delta faces several long-term sustainability challenges. Threats such as levee failure and flooding, ground subsidence,[40] and sea level rise (since the Delta estuary connects freshwater to the Pacific Ocean) pose significant risks to people, infrastructure, and ecosystems.[41] These problems – caused by both land management practices and climate change impacts – are making both agricultural production and ecological restoration in the Delta more challenging. For example, the cultivation of crops such as corn and alfalfa requires a drained root zone, and producing these crops in the Delta requires farmers to drain wet areas. This exposed Delta peat soils to oxygen – which in turn released stored carbon stocks into the atmosphere, further exacerbating climate change, causing ground subsidence,[42] and decreasing land arability.[43] At the same time, climate change is causing sea levels to rise, which increases the risk of levee failure and flooding.[44] Other climate impacts, such as extreme heat and drought, affect the productivity of crops and impact habitat and biodiversity.

Implementing land use changes in the Delta can mitigate climate change, stop and reverse ground subsidence, and support water infrastructure, local economies, and biodiversity. The idea is to slow the decomposition of organic matter by keeping lands perpetually wet and creating anaerobic conditions in soil:[45] instead of cultivating crops that require dry soils and the corresponding drainage of wetlands, lands can be converted to rice cultivation or managed wetlands. To date, several land-use change pilot projects have been undertaken in the Delta, notably on Sherman and Twitchell islands. By constructing wetlands and planting rice, the Sherman and Twitchell projects created a wetland-rice mosaic that delivers economic and ecological benefits while mitigating greenhouse gas emissions (including both CO_2 and methane). Additional wetland-rice pilot projects are planned on Staten Island, Bouldin Island, and Webb Tract. For example, The Nature Conservancy, which owns Staten Island, is in the process of

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[39] United States Environmental Protection Agency, 2023a

[40] Ground Subsidence means sinking of the wetland ground because of the removal of underground water and organic materials (National Oceanic and Atmospheric Administration, 2023).

[41] California Department of Water Resources, n.d.

[42] The subsidence will increase the risk of levee failure, jeopardize California's water supply, and make farming activities less viable by creating increased height differences between island surfaces and adjacent surface-water levels and augmenting hydraulic forces against levees (Deverel et al., 2016).

[43] Pitzer, 2020

[44] Deverel et al., 2015

[45] Hemes et al., 2019

converting 4,000 acres from corn to rice and adjacently restoring 1,000 acres of managed wetland habitat.[46]

It is worth noting that there are economic incentives that can help advance wetland restoration projects in the Delta. Carbon credits are one such incentive; in 2020, the American Carbon Registry issued credits for 52,000 tons of CO_2 removed by wetland restoration projects on Sherman and Twitchell islands.[47] Additional efforts are being made to calculate baseline greenhouse gas emissions across the Delta through the utilization of models and eddy covariance techniques[48] and advance more projects in the voluntary carbon market. For instance, The Nature Conservancy is in the process of applying for carbon offset credits for its rice-wetland project on Staten Island, with its first round of carbon emission reductions anticipated to be verified in 2024.

The Delta serves as an example that can help to inform other geographies and jurisdictions. Best practices from the Delta that might apply to other jurisdictions include the following:

- **Converting agricultural lands to a rice-wetland mosaic** could reduce soil oxidation,[49] thereby reversing ground subsidence, mitigating greenhouse gas emissions, and delivering ecological and biodiversity benefits.
- **Quantifying baseline greenhouse gas emissions through model estimation and eddy covariance techniques** can provide insights into the complex interplay between soils, hydrology, and agricultural production.
- **Incorporating more wetland restoration projects into the carbon market** provides an economic incentive to support landowners and farmers in implementing these projects and improves the long-term financial viability of these projects.

Despite progress, there are many challenges to accelerating wetland restoration projects in the Delta. These roadblocks should be considered and addressed if similar wetland restoration projects are to be implemented in other jurisdictions.

- **Local support**. Converting lands from profitable crops to rice or wetlands may reduce economic revenue for farmers, thereby leading to a lack of support from local farmers. This underscores the need to develop and advance economic incentives, like carbon markets, that can help to compensate for this revenue loss. Continued research, local engagement, and communication with farmers can also help to build the case for the many benefits associated with wetland restoration.

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[46] Hothouse & Ellison, 2022

[47] Hothouse & Ellison, 2022

[48] Eddy covariance is a micro-meteorological method that is currently popular to directly observe the exchanges of gas, energy, and momentum between ecosystems and the atmosphere (Liang et al., 2012).

[49] Soil oxidation means exposing wetland peat soils to oxygen, which in turn released stored carbon stocks into the atmosphere, exacerbating climate change.

- **Low carbon price**. The price of carbon offset credits in the voluntary market is currently too low to cover the loss of profitable crops and the cost of implementing wetland restoration projects. Other financial incentives should be explored and developed to support the economic viability of these projects. Such incentives might include subsidies, among others.

- **High implementation cost**. The conversion of agricultural lands to wetlands is expensive and may require not only construction costs but also costs associated with environmental permitting and prevailing wages, depending on where and how the conversion is being completed. Additionally, the ongoing monitoring of greenhouse gas emissions and estimation of baseline emissions can be costly; both require equipment installation and human resources.

- **Limited understanding of wetland greenhouse gas patterns**. Although there have been great strides, the science underlying greenhouse gas emissions from wetlands remains to be advanced, and there are still open questions about accurately calculating baseline greenhouse gas emissions. These questions additionally add complexity to incorporating wetland restoration projects into carbon markets. More technical research is needed to address this challenge.

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About the California-China Climate Institute

The California-China Climate Institute was launched in September 2019 and is a University of Californiawide initiative housed jointly at UC Berkeley's School of Law (through its Center for Law, Energy, and the Environment) and the Rausser College of Natural Resources. It is Chaired by Jerry Brown, former Governor of the State of California, and Vice-Chaired by the former Chair of the California Air Resources Board Mary Nichols. The Institute also works closely with other University of California campuses, departments, and leaders. Through joint research, training, and dialogue in and between California and China, this Institute aims to inform policymakers, foster cooperation and partnership and drive climate solutions at all levels.

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