© APR 2026 | IRE Journals | Volume 9 Issue 10 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I10-1716792

Teal Carbon And Freshwater Wetland Carbon Dynamics: A Synthesis of Stocks, Sequestration, Emissions, And Methodological Challenges

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Abstract-* Freshwater wetlands are among the most carbon-dense yet threatened ecosystems on Earth. This seminar paper synthesises five peer-reviewed studies on teal carbon quantification, methane emissions from constructed waterbodies, vegetation-mediated carbon sequestration, wetland conversion to agriculture, and methodological challenges in peatland carbon estimation. Peatlands alone store 387–442 Pg C globally — exceeding blue and green carbon systems per unit area. However, methane emissions, land-use conversion, drainage, and biases in carbon accounting substantially reduce their net climate benefit. The paper concludes with recommendations for conservation, restoration, and improved accounting to support nature-based climate solutions.

***Keywords:* teal carbon, peatlands, carbon sequestration, methane emissions, wetland degradation, apparent carbon accumulation rate, natural climate solutions, soil organic carbon.**

I. INTRODUCTION

Inland freshwater wetlands occupy 5–8% of Earth's land surface yet store 20–30% of global soil carbon (Mitsch et al., 2013). Despite this importance, they are being lost at approximately 1.09% per year, driven by agricultural conversion, urban expansion, and hydrological alteration (Davidson, 2014). The concept of "teal carbon" — coined by Nahlik and Fennessy (2016) — describes organic carbon stored in shallow, non-tidal inland freshwater wetlands, including peatlands, marshes, swamps, bogs, fens, and other palustrine and riverine types.

This paper draws on five studies to construct a multi-dimensional understanding of freshwater wetland carbon dynamics. Kumar et al. (2025) provide a comprehensive global synthesis of teal carbon stocks, sequestration rates, and greenhouse gas emissions. Malerba et al. (2022) highlight underestimated methane emissions from agricultural ponds. Whitaker et al. (2015) examine how vegetation persistence and inundation regime govern carbon storage in Australian Phragmites australis reedbeds. Were et al. (2020) document soil organic carbon (SOC) loss following wetland conversion to rice paddies in Uganda. Young et al. (2021) expose a fundamental flaw in the apparent carbon accumulation rate (aCAR), the most widely used peatland carbon metric. Together, these studies reveal a system that is simultaneously a major carbon sink, a significant greenhouse gas source, and a highly vulnerable target for degradation.

II. BACKGROUND: THE TEAL CARBON FRAMEWORK

The colour-based carbon nomenclature distinguishes green carbon (terrestrial forests), blue carbon (tidal coastal ecosystems), and teal carbon (shallow, non-tidal inland freshwater wetlands). Teal carbon ecosystems — classified primarily under the Cowardin et al. (1979) system — include freshwater marshes, bogs, fens, mires, forested and non-forested swamps, peatlands, prairie potholes, and urban or farm ponds.

Their exceptional carbon storage capacity stems from the interplay between high primary productivity and restricted decomposition. Waterlogged, anaerobic soil conditions suppress aerobic decomposer activity, allowing organic matter to accumulate over millennia into deep peat layers (sometimes 15–20 m). The dual role of wetlands as both carbon sinks and sources of methane (CH_4) — with a global warming potential ~28× CO_2 over 100 years (IPCC, 2013) — complicates any simple assessment of their net climate benefit.

III. GLOBAL TEAL CARBON: STOCKS, SEQUESTRATION, AND EMISSIONS

3.1 Spatial Extent and Carbon Stocks

Kumar et al. (2025) synthesised data from 349 studies in the most comprehensive global teal carbon review to date. Natural inland freshwater wetlands cover 11.79–12.79 million km2. Peatlands dominate at ~4.23 million km2 (3.53 million non-forested, 0.70 million forested), concentrated in boreal Asia and North America, with smaller but carbon-dense tropical peatlands in Southeast Asia, Central Africa, and South America.

Carbon stock densities are highest in peatlands (101.63 ± 68.12 kg C m−2), followed by non-tidal freshwater swamps (42.82 ± 40.01 kg C m−2) and marshes (13.97 ± 10.77 kg C m−2). Total global teal carbon storage is estimated at 452–524 Pg C, with peatlands accounting for 387–442 Pg C — roughly twice global forest biomass carbon and nearly equal to the atmospheric CO_2 pool. High peatland carbon density reflects low-temperature/high-moisture conditions in boreal zones and high productivity in tropical systems.

3.2 Carbon Sequestration Rates

Non-tidal freshwater swamps have the highest average soil carbon sequestration rate (216.66 ± 252 g C m−2 yr−1), followed by marshes (180.01 ± 168.66 g C m−2 yr−1) and peatlands (125.53 ± 109.73 g C m−2 yr−1). Scaled to global area, annual teal carbon sequestration — peatlands 531.54 Tg C yr−1, swamps 253.49 Tg C yr−1, marshes 192.61 Tg C yr−1 — collectively surpasses blue and green carbon systems, underscoring teal carbon's primacy as a natural climate solution.

3.3 Greenhouse Gas Emissions

Non-tidal freshwater marshes exhibit the highest CH_4 emissions (104.37 ± 130.82 g C-CH_4 m−2 yr−1), followed by peatlands (68.79 g C-CH_4 m−2 yr−1) and swamps (30.48 g C-CH_4 m−2 yr−1). CO_2 emissions are also substantial, driven primarily by aerobic decomposition during water-table drawdowns. Remote-sensing analysis using Sentinel-5P TROPOMI and GOSAT data confirmed increasing CH_4 and CO_2 concentrations over teal carbon ecosystems between 2019–2021, with highest methane concentrations in the 10°–30°N latitudinal band.

IV. METHANE EMISSIONS FROM AGRICULTURAL PONDS

4.1 Scale of Emissions

Small constructed agricultural ponds — typically 0.01–1 ha — receive fertiliser and manure run-off that drives intense methanogenesis. Malerba et al. (2022) combined mapping data, satellite temperature records, and a meta-analysis of 286 pond flux measurements to estimate that 2.56 million US agricultural ponds emit ~95.8 kt CH_4 yr−1 and 1.76 million Australian ponds emit ~75.1 kt CH_4 yr−1 — equivalent to 4.79 Mt CO_2-e yr−1 combined.

4.2 Discrepancies with National Inventories

US and Australian UNFCCC submissions underestimate agricultural pond emissions by 46% and 54%, respectively. The IPCC recommends a temperature-independent factor of 183 kg CH_4 ha−1 yr−1, but Malerba et al. (2022) found emissions roughly double this at 30°C (~405 kg CH_4 ha−1 yr−1), highlighting the critical need for temperature-sensitive emission factors. Practical mitigation options — livestock fencing around ponds (56% reduction), and phytoremediation buffers — provide feasible near-term interventions.

V. VEGETATION PERSISTENCE, INUNDATION REGIME, AND CARBON STORAGE

5.1 Phragmites australis in the Macquarie Marshes

Whitaker et al. (2015) studied a gradient of Phragmites australis reedbeds in the semi-arid Macquarie Marshes (Murray-Darling Basin, NSW, Australia), ranging from near-annually inundated persistent reedbeds (Transect AB) through seasonally inundated ephemeral reedbeds (Transect CD) to vegetation experiencing prolonged absence of inundation (Transect EF). Aboveground biomass at Transect AB averaged 3,320 ± 777 g m−2 versus 2,760 ± 721 g m−2 at CD, while soil organic carbon (0–100 cm) declined from 170 ± 49 Mg ha−1 (AB) to 140 ± 37 (CD) to 120 ± 37 Mg ha−1 (EF), confirming that inundation frequency drives both above- and belowground carbon accumulation.

5.2 Hydrological Management Implications

Despite higher total SOC, the persistently inundated site exhibited lower recent carbon sequestration rates (~5.17 g C m−2 yr−1) than the ephemeral sites (~554 g C m−2 yr−1 at Transect CD) — attributable to exceptionally rapid sediment accretion at the latter since river regulation in 1967. However, reedbed extent declined ~53,000 Mg in aboveground carbon between 1991 and 2008 following Burrendong Dam construction, and NDVI analyses confirmed substantial recovery after the 2010–2012 wet period. These findings demonstrate that environmental water allocations can restore wetland carbon stocks over short timescales, making them a cost-effective management tool.

VI. IMPACTS OF WETLAND CONVERSION ON SOIL ORGANIC CARBON

6.1 Natural Wetlands versus Rice Paddy Agriculture

Were et al. (2020) compared SOC across three natural vegetation communities (Cyperus papyrus, Typha latifolia, Phragmites mauritianus) and a converted rice paddy section in the Naigombwa wetland, Uganda. Natural communities dramatically outperformed the converted section: mean SOC contents were Papyrus 123.7, Typha 85.3, Phragmites 78.2 versus rice paddy 39.7 g kg−1. SOC storage potentials over 0–50 cm were 361.18, 335.31, and 310.17 Mg ha−1 for the natural communities versus 195.10 Mg ha−1 for rice — reductions of 46%, 42%, and 38% respectively.

6.2 Mechanisms and Broader Implications

Three mechanisms explain the difference: (i) higher net primary productivity in natural macrophytes (Papyrus: 2.51–3.09 kg m−2 yr−1) versus two rice seasons; (ii) greater organic matter recalcitrance due to higher lignin content in macrophytes (22–34%) versus rice (5–15%); and (iii) permanent flooding maintaining anaerobic conditions in natural wetlands versus seasonal drying in paddies promoting aerobic mineralisation. Uganda is currently losing natural wetlands to rice cultivation at ~846 km2 yr−1. The findings make a compelling case for upland rice systems and evidence-based cost-benefit analyses before further wetland conversion.

VII. METHODOLOGICAL CHALLENGES: LIMITATIONS OF APPARENT CARBON ACCUMULATION RATE (ACAR)

7.1 The aCAR Problem

Young et al. (2021) present a systematic critique of aCAR — calculated by dividing the carbon content of a dated peat layer by its age — arguing it cannot serve as a reliable proxy for true net carbon balance (NCB). Two fundamental flaws are identified. First, an "ageing" problem: ongoing post-depositional decomposition causes older layers to have lost more carbon than younger ones, artificially inflating near-surface aCAR values regardless of actual accumulation trends. Second, the "acrotelm effect": near-surface peat, having undergone less decomposition, appears to accumulate rapidly — creating a spurious signal of accelerating carbon uptake.

7.2 The Misuse of RERCA and Implications

RERCA (Recent Rate of Carbon Accumulation), which treats the acrotelm as a single dated layer, is mathematically flawed: it estimates mass at one time point rather than the change in mass over time, producing systematically inflated accumulation estimates that can even give the wrong sign — indicating net gain when a peatland is actually losing carbon. DigiBog simulations confirm that a drought causing net carbon loss produces no negative aCAR values, only lagged near-surface reductions. Young et al. (2021) recommend fitting process-based models (e.g. Holocene Peat Model, MILLENNIA, DigiBog) to peat core age-depth data, ideally combined with eddy covariance flux measurements, to reliably reconstruct NCB. This critique has direct implications for national carbon accounting and voluntary carbon markets that rely on aCAR-based peatland assessments.

VIII. SYNTHESIS AND DISCUSSION

8.1 Climate Significance and Greenhouse Gas Trade-offs

The reviewed studies collectively confirm that freshwater wetlands are the most carbon-dense terrestrial ecosystems on Earth, with annual sequestration potential exceeding blue and green carbon systems. However, they are also significant CH4 sources. Agricultural ponds alone contribute ~4.79 Mt CO2-e yr−1 beyond what national inventories report, illustrating the ongoing incompleteness of global wetland greenhouse gas accounting.

8.2 Threats and Degradation

Hydrological alteration and land-use conversion degrade teal carbon stocks rapidly. River regulation reduces reedbed extent and soil carbon over decades (Whitaker et al., 2015); agricultural conversion reduces SOC by 38–46% within the uppermost 50 cm (Were et al., 2020). Global wetland losses of 1.09% yr−1, concentrated in tropical regions, translate to enormous carbon emissions as aerobic decomposition of previously anaerobic organic matter can ultimately release up to 96% of stored SOC.

8.3 Conservation, Restoration, and Teal Carbon Zones

Kumar et al. (2025) propose Development of Self-sustaining Teal Carbon Zones (DSTCZ) — shallow wetland habitats with appropriate vegetation — to maximise sequestration while delivering co-benefits (water security, flood mitigation, biodiversity, urban cooling). Evidence supports restoration efficacy: rehabilitated prairie pothole wetlands reach 60–80% of reference SOC within 5–12 years; Macquarie Marsh reedbeds recovered substantially within three years of increased inundation. Environmental water allocations are a particularly cost-effective restoration mechanism in regulated river systems.

8.4 Improving Carbon Accounting

aCAR-based peatland carbon estimates are systematically biased (Young et al., 2021), and agricultural pond inventories are approximately 50% too low (Malerba et al., 2022). Addressing these gaps requires expanded eddy covariance monitoring networks, large-scale pond temperature surveys, and validated process-based models. Including temperature sensitivity in IPCC emission factors for constructed waterbodies is an immediate and achievable reform.

IX. CONCLUSION

This synthesis yields five principal conclusions. First, peatlands alone store 387–442 Pg C, and annual teal carbon sequestration exceeds that of blue and green carbon combined, placing freshwater wetlands at the centre of nature-based climate strategies. Second, these ecosystems are also major CH4 sources, and agricultural pond emissions are approximately double current UNFCCC inventory estimates. Third, inundation frequency and hydrological connectivity fundamentally control both above- and belowground carbon stocks; environmental water allocation is an effective and rapid restoration tool. Fourth, conversion of natural tropical wetlands to rice agriculture reduces SOC storage potential by 38–46%, arguing strongly for non-wetland-dependent agricultural intensification. Fifth, aCAR cannot reliably estimate peatland net carbon balance and must be replaced by process-based modelling in scientific and policy contexts.

Recommended actions: (i) prioritise conservation of intact freshwater wetlands as the most cost-effective climate strategy; (ii) implement environmental water allocation programmes in regulated river systems; (iii) promote DSTCZ development as a scalable nature-based solution; (iv) revise national greenhouse gas inventories to incorporate temperature-sensitive agricultural pond emission factors; (v) phase out aCAR as a primary metric in favour of process-based modelling; and (vi) substantially increase investment in long-term wetland carbon flux monitoring networks.

REFERENCES

[1] Cowardin, L.M., Carter, V., Golet, F.C. and LaRoe, E.T. (1979). Classification of

Wetlands and Deepwater Habitats of the United States. U.S. Fish and Wildlife Service, FWS/OBS-79/31.

[2] 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(10), 934–941.

[3] Davidson, N.C., Fluet-Chouinard, E. and Finlayson, C.M. (2018). Global extent and distribution of wetlands. Marine and Freshwater Research, 69(4), 620–627.

[4] Gardner, R.C. and Finlayson, M. (2018). Global Wetland Outlook 2018. Ramsar Convention Secretariat, Gland, Switzerland.

[5] IPCC (2013). Climate Change 2013: The Physical Science Basis. Cambridge University Press.

[6] Kumar, S., Sharma, L.K. and Fennessy, M.S. (2025). Global teal carbon: Stocks, sequestration, and its potential role in climate change mitigation. Science of the Total Environment, 995, 180128.

[7] Malerba, M.E., de Kluyver, T., Wright, N., Schuster, L. and Macreadie, P.I. (2022). Methane emissions from agricultural ponds are underestimated in national greenhouse gas inventories. Communications Earth & Environment, 3(1), 306.

[8] Mitsch, W.J. et al. (2013). Wetlands, carbon, and climate change. Landscape Ecology, 28(4), 583–597.

[9] Nahlik, A.M. and Fennessy, M.S. (2016). Carbon storage in US wetlands. Nature Communications, 7, 13835.

[10] Were, D., Kansiime, F., Fetahi, T. and Hein, T. (2020). A natural tropical freshwater wetland is a better climate change mitigation option through soil organic carbon storage compared to a rice paddy wetland. SN Applied Sciences, 2(5), 951.

[11] Whitaker, K., Rogers, K., Saintilan, N., Mazumder, D., Wen, L. and Morrison, R.J. (2015). Vegetation persistence and carbon storage. Water Resources Research, 51(7), 5284–5300.

[12] Young, D.M., Baird, A.J., Gallego-Sala, A.V. and Loisel, J. (2021). A cautionary tale about using the apparent carbon accumulation rate (aCAR) obtained from peat cores. Scientific Reports, 11, 9547.