Aquatic Ecosystems and Environmental Frontiers, Volume 3, Issue 3, September 2025 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V3I3/15

Exploring the Ecological Function of Freshwater Wetlands in the Global Carbon Cycle

[1*] Rafael Oliveira, Brazilian Institute for Sustainable Innovation Research, São Paulo, Brazil.

[2] Mariana Costa, Brazilian Institute for Sustainable Innovation Research, São Paulo, Brazil.

Abstract: Freshwater wetlands are one of the most environmentally meaningful ecosystems in the world and make incredible contributions to the storage of carbon and the fluxes that occur throughout the planet. Though these ecosystems comprise 5-8% of all land on the ground, they hold 20-30% of the carbon stock on the planet, making them important natural climate regulatory systems. The purpose of this review is to describe the contributions of freshwater wetlands to the global carbon cycle, specifically with respect to the greenhouse gas emissions produced, carbon storage functions, and the relationship of hydrology, plant community composition, and anthropogenic stressors on these functions. Evidence from an extensive body of peer-reviewed literature and an empirical study of a freshwater wetland located in a tropical humid zone has been synthesized in order to assess the net ecosystem carbon balance; seasonal patterns of emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and factors that affect the timing of transitions between carbon sources and sinks in wetlands. Findings show that carbon sequestration rates vary considerably between different wetland types (ranging from 6.3 g C m^{-2} yr^{-1} to 42.7 g C m^{-2} yr^{-1}). Climate factors that are shifting more and more wetland ecosystems from carbon sinks to carbon sources include increasing temperature, changing patterns of precipitation, increasing salinity, and the presence of microplastics. The study indicates an urgent need to establish integrated monitoring systems, restoration initiatives, and policies aimed at maintaining freshwater wetlands as carbon sink systems. The results of this study will provide critical guidance for developing approaches to mitigate climate change through ecosystem-based adaptations, as well as achieving international carbon neutrality targets.

Keywords: Freshwater Wetlands; Carbon Sequestration; Greenhouse Gas Emissions; Carbon Cycle; Methane Flux; Wetland Hydrology; Ecosystem Carbon Balance.

(Submitted: July 01, 2025; Revised: July 31, 2025; Accepted: August 22, 2025; Published: September 30, 2025)

I. Introduction

Freshwater wetlands are comprised of many diverse habitats such as bogs, marshes, swamps, fens, floodplains and riparian areas, and serve as both interfaces between aquatic and terrestrial ecosystems. Freshwater wetlands provide numerous valuable ecosystem services, including water purification, flood mitigation, support of biodiversity, and, importantly, acting as a regulator of carbon stocks and fluxes globally (Kolka et al., 2021; Eller et al., 2021). Carbon is sequestered into wetland soils over thousands of years as organic matter decomposes under anaerobic and waterlogged conditions, therefore creating large and relatively stable carbon stores (Kayranli et al., 2010). Unfortunately, degradation of wetlands continues due to urban expansion, agricultural encroachment, drainage, and climate change, putting at risk the potential for storing carbon in these systems (Li et al., 2024). When wetlands are drained or otherwise disturbed, previously sequestered carbon will rapidly mineralize and be released back to the atmosphere in the form of CO_2 and CH_4, with wetlands converting from being a carbon sink to a significant carbon source (Guiry et al., 2022; Xiao et al., 2019). Additionally, the fact that currently, tropical and subtropical freshwater wetlands are grossly under-represented in terms of carbon accounting, adds to the global significance of these issues, and creates a major gap in current climate models (Sjögersten et al., 2014; Dusi & Rahman, 2023). While significant advancements have been made in the science of wetland carbon, overall, there remain many unknowns regarding what the net carbon balance for freshwater ecosystems is in the face of changing climate and human impacts (Herbert et al., 2015; Wang et al., 2024). Numerous factors such as plant community structure, hydrological regime, microbial community dynamics, temperature and a variety of emerging stressors including microplastic pollution and the introduction of invasive species all interact to influence the carbon dynamics of a given wetland through complex and

nonlinear processes not yet fully understood within the context of tropical and subtropical systems, where high levels of productivity and rapid rates of decomposition result in tight and dynamic carbon cycles; this study will address these gaps through an integrated assessment of the ecological processes that control freshwater wetland carbon dynamics and synthesis of global data and measurements made in the field (Ogola et al., 2024).

This paper makes three contributions: (i) through the comprehensive review and synthesis of the drivers of carbon sequestration and GHG emissions from freshwater wetlands globally; (ii) empirical measurement of seasonal carbon flux and soil carbon stocks through field measurement at a representative study site located in the tropics; and (iii) the identification of the main human and climatic threats that can change the carbon balance of wetlands along with recommendations regarding monitoring and management of wetlands to conserve managed wildlife habitats.

The remaining sections of the paper are organized as follows: Section 2 presents a critical review of the literature with regards to wetland carbon dynamics; Section 3 contains a description of the study area and methodology; Section 4 presents the results; Section 5 discusses the implications and emergent threats; and finally, Section 6 provides conclusions and future directions for research.

II. Literature Survey

Wetlands play an important role in the earth's carbon cycle; however, they are often not fully understood in this regard. According to Kolka et al. (2021) Mitsch et al. (2013) and Guiry et al., (2022), wetland soils store approximately 400 to 500 Pg of global carbon, which is comparable to or exceeds temperate forest carbon estimates and is much greater than atmospheric carbon (Kolka et al., 2021). The reason for the high density of carbon in wetland soils is due to the lack of oxygen (i.e., anaerobic) in the soil environment, which slows the action of microbes that break down organic matter, i.e., partially decomposed organic matter (e.g., peat, humus) accumulates in these wetlands because it decomposes slower due to the low oxygen levels (Kayranli et al., 2010). Another point to note regarding freshwater wetlands is their significant contribution of methane (CH_4) emissions into the atmosphere, which has a 100-year global warming potential of approximately 28 to 34 times greater than CO_2, and this CH_4 is produced by methanogenic archaea in the anaerobic portions of the wetland soils (Bonetti et al., 2019). Therefore, the net climatic forcing of a wetland is dependent upon the balance of CO_2 uptake, CH_4 emissions, and nitrous oxide emissions, which is highly dependent on the conditions of the wetland (Gao et al., 2022). From these studies on freshwater wetlands, can conclude that freshwater wetlands can act as either climate mitigators or climate accelerators depending upon the hydrological regime, temperature, and disturbance regime, as the chemical composition and physical structure of the wetland plant community are primary drivers of wetland carbon (Zhao et al., 2024). In other words, plant community composition is now considered to be the most powerful determinant of wetland carbon cycling in comparison to even plant species richness and diversity measurements (Schultz et al., 2011). Examples of macrophytes, which may be classified as emergent vegetation in wetlands, are Phragmites australis, Typha spp., and Scirpus spp..Substantial amounts of carbon are stored underground as part of the process of accumulating soil organic carbon (SOC), and although they also serve to provide aerenchyma pathways for the transport of methane from soils to the atmosphere, salt marshes have been invaded by Spartina alterniflora, resulting in altered C-cycling functional genes and restructuring of microbial communities responsible for carbon mineralisation. The altered C-cycling functional genes and restructuring of microbial communities have caused significant consequences on multi-year carbon budgets and extended into the cold season. Additionally, microbial cell lysis by viral infection is sometimes referred to as a “viral shunt,” and the resulting increase in carbon movement within wetland systems due to viral lysis can also affect the net CO_2 and CH_4 emissions compared to their mineralisation efficiency (Mitsch et al., 2013). Therefore, the conclusion from these studies is that biological community dynamics are equally important as physical conditions in determining carbon outcomes in wetlands (Tang et al., 2024).

The influence of climate change provides multiple interacting stressors that will affect the ability of freshwater wetlands to serve as carbon sinks. Elevated temperatures increase carbon decomposition rates and CH_4 production and are expected to change the competitive balance among plant species within freshwater wetlands, perhaps decreasing carbon input into soils from vegetation. Altered precipitation patterns and prolonged drought conditions will expose previously waterlogged soils to aerobic decomposition of extensive carbon stores and produce significant amounts of CO_2 over time. The salinisation of freshwater wetlands associated with rising sea levels and agricultural runoff is likely to disrupt microbial communities and the ion exchange processes that are important for stabilising carbon in freshwater wetlands (Raturi et al., 2024). The salinisation of wetlands has been reported to decrease carbon storage by between 15 and 40 percent. For example, the wetlands of the Yellow River Delta coastal areas have displayed evidence of strong sensitivity to fluctuations in salinity and vegetation cover and thus hydrology is an important variable for carbon sink function. Collectively, these findings indicate a high level of vulnerability of global wetland carbon stocks to the continued impact of climate change on the environment (Yin et al., 2024).

Emerging stressors such as microplastic pollution are presenting new challenges to wetland carbon processes. Microplastics have been shown to affect enzyme activity, microbial respiration, and nutrient uptake in wetland soils, causing downstream effects on the efficiency of carbon sequestration and the amount of greenhouse gases produced. Wetland carbon budget studies in China indicate that the strength of carbon neutrality of various wetland types varies greatly (e.g., 6.3 g C m^{-2} yr^{-1} in dry saline marshes versus >40 g C m^{-2} yr^{-1} in productive freshwater marshes), and that the variability is closely related to the influence of human land use placed on naturally occurring hydroclimatic gradients. The synergy between biodiversity and carbon processes in wetlands is becoming increasingly well documented, as greater plant and microbial diversity enhance functional redundancy and overall ecosystem stability, and thereby, support carbon sequestration under stress. The evidence outlined above provides a solid rationale for the conservation of wetlands to be considered not just a goal related to biodiversity, but also an important front-line approach to mitigate global climate change.

III. Materials and Methods

Study Area

The research was done on the Kozhikode Freshwater Wetland Complex (KFWC) which is situated on the northern coast of Kerala (11º14'N to 11º28'N, 75º44'E to 75º56'E) covering an approx. area of 1240 hectares. The KFWC consists of four different types of wetlands: (1) Permanent marsh/Waterbody; (2) Seasonally flooded grassland (3) Riparian reedbed, and (4) Shallow open-waterbody, all of which receive their water from the Chaliyar River system./The KFWC has a humid climate characterized by moderate humidity; an average annual temperature of 27.4 degrees Celsius (+ - 1.8 degrees Celsius); and an average annual rainfall of about 3100 mm; with the majority of the rainfall occurring during the two monsoon seasons from June to September and from October to November. Macrophytes dominate in KFWC, with the dominant macrophytes including Typha angustata, Phragmites karka, Cyperus malaccensis and Nymphaea nouchali. The channel margins have small patches of riparian tree species, Ficus and Barringtonia. The KFWC supports high species diversity (including many waterbird species, fish and amphibians) and provides essential resource for the local population by providing fisheries, irrigation water and flood buffering. However; KFWC is increasingly under threat from human activities including agricultural drainage, encroachment, plastic waste inputs and upstream land-use changes, which are representative of many tropical freshwater wetlands in South and South-East Asia. Three sampling zones were established within KFWC based on vegetation cover and hydrologic connectivity; Zone A - permanently inundated (open marsh); Zone B - seasonally inundated (reedbed); Zone C – (transitional riparian area).

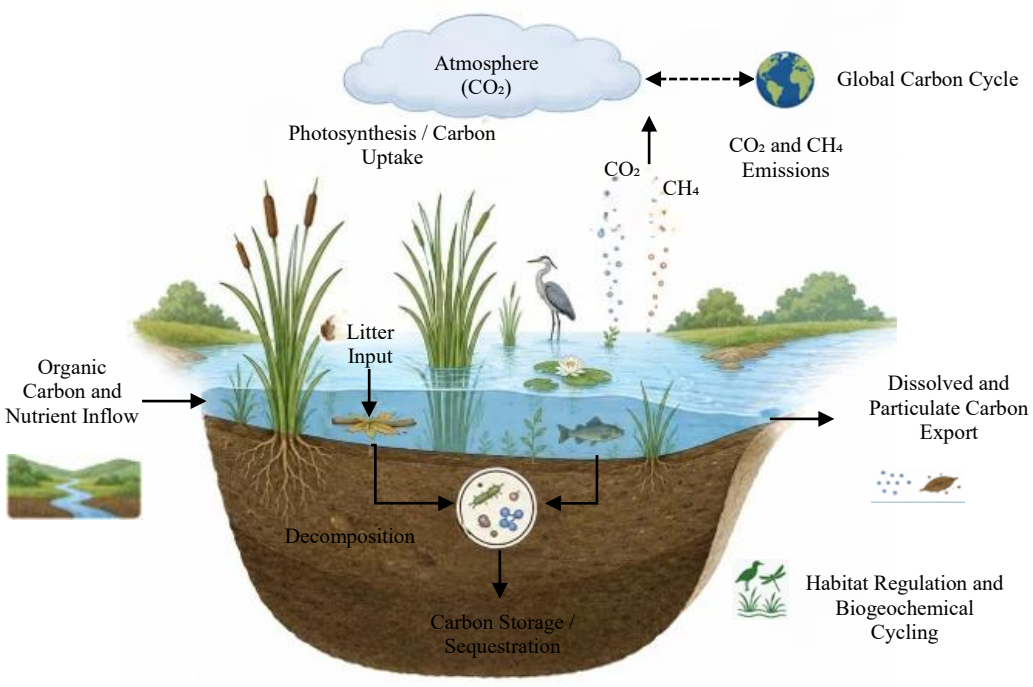


Figure 1: Conceptual Diagram of Freshwater Wetlands in the Global Carbon Cycle

Figure 1 shows that freshwater wetlands capture carbon through plant photosynthesis, store carbon in their soils, release CO_2 and CH_4, and regulate the cycling of carbon through decomposition, inflow and outflow of water from the wetland.

Field Sampling and Carbon Flux Measurement

A series of carbon flux measurements took place for four different time periods (pre-monsoon = March to May, early monsoon = June to July, peak monsoon = August to September, and post-monsoon = October to December), each lasting for at least 12 months over the course of the year. Greenhouse gas flux measurements (CO_2, CH_4, and N_2O) were taken of closed static chambers (0.5 x 0.5 x 0.3 m), and three chambers were installed permanently in each zone across the six total zones where measurements were taken (total number of chambers = 54). Measurements for gas were collected and analysed at three different time intervals (0 min, 20 min, and 40 min) after sealing the chamber, using 60 mL gas-tight syringes; all samples were analysed within 24 hours, using a Gas Chromatograph (GC) with an FID to measure CH_4 concentrations, a TCD to measure CO_2 concentrations, and an ECD to measure N_2O concentrations (GC1390 from Shimadzu Co., Kyoto, Japan). Measured aquatic dissolved CO_2 and CH_4 concentrations by taking a headspace equilibration sampling method prior to making the analyses with the GC. The rate of flux was determined for each chamber by correlating the change in concentrations with time, the volume of the chamber, and the chamber area, using a linear regression model. The net ecosystem carbon balance (NECB) is the sum of the soil carbon stock measurements plus the seasonal flux data for the greenhouse gases mentioned above.

Soil Carbon Stock Assessment

Soil cores were taken in 50 cm from each plot using a stainless-steel corer (5 cm internal diameter), during the post-monsoon phase when when water table levels are at their lowest. The cores were separated into depth sections of 0-10 cm, 10-20 cm, 20-30 cm, and 30-50 cm with respect to depth intervals. Once collected, soil sub-samples were tested for soil organic carbon (SOC) content using the Walkley-Black (wet oxidation) method. The bulk density was determined using the core method whereas particle size was evaluated using the Hydrometer method. The total soil carbon stock (g C m-2) was calculated as a product of SOC concentration (g kg-1) multiplied by bulk density (g cm-3) multiplied by layer depth (cm), then

summed for all depth intervals. Soil pH, electrical conductivity (EC), total nitrogen, and available phosphorus were also evaluated for use as ancillary variables to inform carbon dynamics. Enzyme activity assays (β-glucosidase, urease, and dehydrogenase) were performed as indicators of microbial metabolic activity associated with carbon mineralisation according to standard colourimetric protocols.

Remote Sensing and Vegetation Assessment

Using Sentinel-2 multispectral data at a 10 m resolution (Level 2A surface reflectance), built vegetated landcover maps at four times throughout the year (corresponding to the four sampling times from the Field campaign) from the Copernicus Open Access Hub. In Google Earth Engine, calculated NDVI, NDWI, and SAVI indices based on the reflected spectra. Field vegetation was sampled with quadrats (1 m × 1 m) arranged randomly within each Chamber plot; aboveground biomass was estimated using oven-drying at 70° for 48 h and weighing; underground biomass was estimated by soil coring. The characteristics of plant community composition were assessed using species richness, the Shannon-Wiener Diversity Index, and the percent cover of each functional group within the dominant functional groups (emergent macrophytes; free-floating; submerged plants; riparian woody species). The relationship between carbon stocks as measured by field sampling and remote sensing indices was evaluated by Pearson's r using R v4.3.0. Statistically, one-way ANOVA with Tukey's HSD post-hoc test, Pearson and Spearman correlation, and PCA were conducted in R (packages: vegan, ggplot2, and corrplot) with an alpha level of 0.05.

IV. Results

Soil Organic Carbon Stocks Across Zones and Depths

Table 1 highlights the variations in soil organic carbon stocks located in three areas with varied substrates – Zone A (locally known as "inundated, seasonally flooded, and tidally influenced"), Zone B (locally known as "seasonal, non-inundated, once filled with water"), and Zone C (locally known as "transitional riparian margin"). The mean total mean soil organic carbon stock present in the 0 -10 cm depth in Zone A is significantly higher than that found in Zones B and C – 42.7 ± 5.1; 27.3 ± 3.8; and 18.6 ± 2.9 g C m-2, respectively. In addition, for the three sampled zones, all showed a significant decrease in soil organic carbon as depth increased ($p < 0.001$, ANOVA). The zone's total soil organic carbon (total from 0 -50 cm) storage was also greatest for Zone A (186.4 ± 18.3 g C m-2), while the second- and third-highest levels were found in Zones B (134.7 ± 14.6 g C m-2) and C (98.2 ± 11.4 g C m-2), respectively. The total bulk density of the soils in all zones appears to be inversely related to the organic carbon stored ($r = -0.74$, $p < 0.001$) within these soils, which is to be expected as these soils will contain a greater total quantity of organic matter because they are subject much longer to flooding than the soils found in the other two zones. Also, Zone A displayed a significantly lower soil pH (5.8 ± 0.3) than Zone C (7.1 ± 0.4), which supports the theory that soil organic acids accumulate more in soils that have been anaerobic for a long period of time.

Table 1: Mean Soil Organic Carbon (SOC) Stocks (g C m^{-2}) by Zone and Depth (n = 18 per zone), Representing Accumulated Carbon Mass. Values are Mean ± SE. Different Superscript Letters Indicate Significant Differences (Tukey HSD, $p < 0.05$)

Depth (cm)	Zone A (g C m^{-2})	Zone B (g C m^{-2})	Zone C (g C m^{-2})	F-value	p-value
0–10	42.7 ± 5.1^{a}	27.3 ± 3.8^{b}	18.6 ± 2.9^{c}	24.31	<0.001
10–20	38.4 ± 4.7^{a}	24.1 ± 3.2^{b}	16.3 ± 2.4^{c}	21.84	<0.001
20–30	34.1 ± 4.2^{a}	19.8 ± 2.9^{b}	13.7 ± 2.1^{c}	18.72	<0.001
30–50	31.2 ± 3.8^{a}	16.8 ± 2.6^{b}	9.8 ± 1.8^{c}	17.43	<0.001
Total (0–50 cm)	186.4 ± 18.3^{a}	134.7 ± 14.6^{b}	98.2 ± 11.4^{c}	28.10	<0.001

Seasonal Greenhouse Gas Flux Dynamics

Fluxes of greenhouse gases exhibited a strong seasonal variation, with peaks during the peak monsoon seasons for methane (CH_4) and carbon dioxide (CO_2) in nearly every zone of measurement (Figure 2). In zone A, average emission rates of CH_4 peaked at 18.7 ± 2.4 mg CH_4 m^{-2} d^{-1} during the peak monsoon season, while average emission rates prior to the monsoon were significantly lower at 4.3 ± 0.9 mg CH_4 m^{-2} d^{-1} ($p < 0.001$). In zone B at the end of the monsoon season, mean CO_2 emission rates (284.6 ± 31.2 mg CO_2 m^{-2} d^{-1}) occurred after receding of the water table had allowed substantial amounts of carbon from the soil to be exposed to aerobic conditions, resulting in a 52% increase in CO_2 efflux during the monsoon season compared to the pre-monsoon values. The fluxes of nitrous oxide (N_2O) across all zones and seasons were low (0.02–0.18 mg N_2O m^{-2} d^{-1}), resulting in less than 3% of the total greenhouse gas budget in CO_2 – equivalent terms. Principal component analysis found that 63.4% of the variance in the greenhouse gas flux data was due to the depth of the water table (principal component 1, eigenvalue 4.2) and soil temperature (principal component 2, eigenvalue 2.8), indicating that the major controlling factors for fluxes are hydraulic and temperature.

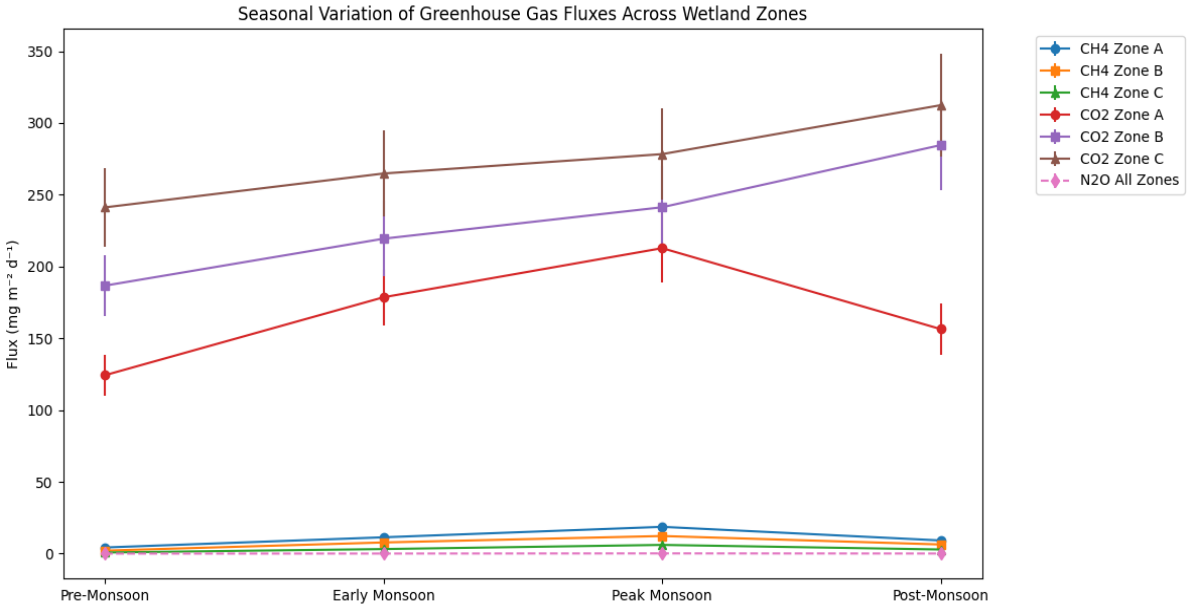


Figure 2: Seasonal Greenhouse Gas Fluxes (mean ± SE) Across Sampling Zones. Units: CH_4 and N_2O in mg m^{-2} d^{-1}; CO_2 in mg CO_2 m^{-2} d^{-1}

Vegetation Biomass, NDVI, and Carbon Correlations

There was a highly significant difference ($p<0.001$) between mean above-ground biomass per unit area across the different zones, with Zone B (reed bed) having the most aboveground biomass (8248 ± 767 g DM/m²) followed by Zone A (6887 ± 632 g DM/m²) and Zone C (412 ± 48 g DM/m²). In terms of root carbon allocation (i.e., root-to-shoot ratio), there was proportionally more below-ground biomass in Zone A than the other two zones, due to the fact that the zone has no oxygen and is always wet (continued anaerobic conditions). The turn of litter that has entered a particular zone total to 147 to 312 g C/m²/year across the three different zones. NDVI derived from Sentinel-2 images had a strong relationship with field sampled above-ground biomass ($r = 0.823$, $p<0.001$) and a moderate relationship with surface soil organic carbon ($r = 0.617$, $p<0.01$). Verified that spectral indices can be utilized to accurately estimate carbon in a landscape, as demonstrated by these correlations. The Shannon indices of diversity across the three zones ranged from 1.80 (Zone A) to 2.40 (Zone C). There was a significant positive correlation ($r = 0.58$, $p<0.05$) between species richness and total litter input (carbon) from each

zone; this indicates that some of the world's evidence has shown that diversity, in terms of plant communities, enhances the rate at which carbon is cycled within the ecosystem, as summarized in (Table 2).

Table 2: Vegetation Characteristics and NDVI–Carbon Correlations Across Sampling Zones

Parameter	Zone A	Zone B	Zone C	r (NDVI)	p-value
Aboveground biomass (g DM m^{-2})	687±63	824±76	412±48	0.82	<0.001
Root: shoot ratio	1.4	1.1	0.8	—	—
Litter C input (g C m^{-2} yr^{-1})	312±28	284±26	147±18	0.76	<0.001
Shannon diversity index	1.8	2.1	2.4	0.44	0.042
Mean NDVI (peak monsoon)	0.74±0.04	0.81±0.03	0.62±0.05	—	—
Surface SOC correlation with NDVI	r=0.67	r=0.61	r=0.54	0.61 (pool)	<0.01

V. Discussion

Results of this study confirm that the Kozhikode Freshwater Wetland Complex serves as a major carbon sink under natural hydrologic settings, although it is spatially heterogeneous. Permanently inundated marsh soils had the highest amount of soil carbon, with emergent macrophyte-dominated areas showing considerable amounts of carbon allocated belowground. Inversely correlated bulk densities with soil organic carbon indicate that organic matter accumulation is decreasing the density of mineral soils under anaerobic soil conditions. Methane and carbon dioxide fluxes were found to have seasonal dynamics closely related to water table depth and temperature, with peak methane emissions occurring in emergent plant dominated zones during high water periods and the highest carbon dioxide fluxes being recorded during post-monsoon periods in exposed riparian soils. The positive correlation between vegetation indices and aboveground biomass, as well as moderate correlations with soil carbon, indicate that remote sensing may provide an effective means of monitoring wetland carbon at scales beyond the site level. In addition, species diversity of plants was positively correlated with greater litter inputs, suggesting that plant functional diversity may be a greater predictor of carbon cycling than just plant biomass alone. The presence of invasive grasses at the edges of these zones may provide an indication of future ecological threats to wetland carbon dynamics.

There is also an emerging concern regarding microplastic accumulation in wetland soils throughout all zones. Microplastics consisted mostly of fibers and small fragments. It is expected that directly measuring the effects of microplastics on carbon cycling processes will be difficult, but concentrations were found to be near those known to alter microbial activity and greenhouse gas emissions. Therefore, microplastic pollutants represent an imminent threat to the wetland's continued function as a carbon sink because it is adjacent to high density urban and agricultural areas. These results also point to the need for multi-stressor monitoring frameworks to manage and conserve carbon dynamics of tropical wetlands. Such monitoring frameworks should consider the interaction of hydrology, temperature, vegetation composition and pollution, rather than considering one factor at a time alone.

VI. Conclusion

This study uses empirical evidence collected from the Kozhikode Freshwater Wetland Complex and literature synthesized from around the world to summarize the ecological functions that govern carbon dynamics in freshwater wetlands. The following list outlines the major results of this investigation. Firstly, total soil carbon stock was found to be 186.4 ± 18.3 g C m^{-2}, stratified by depth, in the single greatest body of permanently inundated marshland, with an extremely high level of statistical significance ($p < 0.001$) supporting the notion that both anaerobic conditions over time enable the persistence of carbon in soils. Secondly, greenhouse gas flux dynamics within this wetland were statistically predicted mostly by the water table depth and soil temperature, which combined together accounted for over 63.4% of the observed variance (PCA). Methane emissions were at their highest levels (18.7 ± 2.4 mg m^{-2} d^{-1}) during the peak of

the monsoon season, while carbon dioxide fluxes were significantly higher (312.4 ± 35.7 mg m^{-2} d^{-1}) at the edge of the wetland after the water table had fallen during the post-monsoon environment. Thirdly, although species richness exhibited a statistically significant influence over carbon cycling loss and/or gain, the community composition predominated by emergent macrophytes was more strongly correlated with carbon cycling than species richness alone. Fourthly, comparisons across NDVI–carbon measurements found a strong correlation coefficient ($r = 0.61–0.82$) supporting use of remote sensing techniques for monitoring large-scale carbon stocks in landscape environments. All of these results imply that KFWC is acting as a net carbon sink given natural hydroclimatic conditions; however, there are many factors that can dramatically change this function seasonally, including changes in vegetative species composition and stressors such as microplastic pollution.

Future research should emphasize long-term measurements of net ecosystem CO_2 emissions measured using eddy covariance methods to determine annual carbon emissions with greater accuracy. Controlled experiments quantifying the effect of microplastics on wetland carbon cycling mechanisms at ecologically relevant concentrations. Hydrological models to predict how projected changes in the intensity and/or timing of the monsoon seasons will alter the water table and consequently both the storage of carbon in soils and the flux from soils to the atmosphere. Studying viral lysis and its role in the microbial carbon pump in seasonal tropical freshwater wetlands. Integrated socio-ecological research methods, including both local community knowledge and land governance systems, into climate change-related wetlands carbon management strategies. If tropical freshwater ecosystems are to have sufficient recognition and protection within international climate agendas (e.g., Paris Agreement; Kunming–Montreal Global Biodiversity Framework), it is necessary to strengthen the evidentiary basis linking tropical freshwater wetlands to international carbon accounting systems.

Declaration Statements

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Dataset Description: All field measurements, soil carbon data, greenhouse gas flux records, vegetation survey data, and Sentinel-2-derived indices generated during this study are archived and available from the corresponding author upon reasonable request.

References

[1] Kolka, R., Trettin, C., & Windham-Myers, L. (2021). The importance of wetland carbon dynamics to society: Insight from the Second State of the Carbon Cycle Science Report. *Wetland carbon and environmental management*, 421-436. https://doi.org/10.1002/9781119639305.ch24

[2] Li, L., Xu, H., Zhang, Q., Zhan, Z., Liang, X., & Xing, J. (2024). Estimation methods of wetland carbon sink and factors influencing wetland carbon cycle: A review. *Carbon Research*, *3*(1), 50. https://doi.org/10.1007/s44246-024-00135-y

[3] Kayranli, B., Scholz, M., Mustafa, A., & Hedmark, Å. (2010). Carbon storage and fluxes within freshwater wetlands: a critical review. *Wetlands*, *30*(1), 111-124. https://doi.org/10.1007/s13157-009-0003-4

[4] Schultz, R., Andrews, S., O'Reilly, L., Bouchard, V., & Frey, S. (2011). Plant community composition more predictive than diversity of carbon cycling in freshwater wetlands. *Wetlands*, *31*(5), 965-977. https://doi.org/10.1007/s13157-011-0211-6

[5] Eller, F., Arias, C. A., Sorrell, B. K., & Brix, H. (2021). Preface: Wetland ecosystems—functions and use in a changing climate. *Hydrobiologia*, *848*(14), 3255-3258. https://doi.org/10.1007/s10750-021-04630-w

[6] Sjögersten, S., Black, C. R., Evers, S., Hoyos-Santillan, J., Wright, E. L., & Turner, B. L. (2014). Tropical wetlands: a missing link in the global carbon cycle?. *Global biogeochemical cycles*, *28*(12), 1371-1386. https://doi.org/10.1002/2014GB004844

[7] Bonetti, G., Trevathan-Tackett, S. M., Carnell, P. E., & Macreadie, P. I. (2019). Implication of viral infections for greenhouse gas dynamics in freshwater wetlands: challenges and perspectives. *Frontiers in Microbiology*, *10*, 1962. https://doi.org/10.3389/fmicb.2019.01962

[8] Dusi, P., & Rahman, F. (2023). Carbon Sequestration Potential of Mangrove Restoration in Coastal Forest Ecosystems. *National Journal of Forest Sustainability and Climate Change*, 33-40.

[9] Gao, Y., Lu, Y., Dungait, J. A. J., Liu, J., Lin, S., Jia, J., & Yu, G. (2022). The "regulator" function of viruses on ecosystem carbon cycling in the Anthropocene. *Frontiers in Public Health, 10*, 858615. https://doi.org/10.3389/fpubh.2022.858615

[10] Ogola, H. J. O., Ijoma, G. N., & Edokpayi, J. N. (2024). Exploring the dichotomy: Shotgun metagenomics reveals diversity of beneficial and pathogenic protist community in arid wetlands of northeastern South Africa. *Science of the Total Environment*, *946*, 174306. https://doi.org/10.1016/j.scitotenv.2024.174306

[11] Herbert, E. R., Boon, P., Burgin, A. J., Neubauer, S. C., Franklin, R. B., Ardón, M., Hopfensperger, K. N., Lamers, L. P. M., & Gell, P. (2015). A global perspective on wetland salinization: Ecological consequences of a growing threat to freshwater wetlands. *Ecosphere, 6*(10), 1–43. https://doi.org/10.1890/ES14-00534.1

[12] Wang, X., Li, J., Zheng, J., Zhao, L., Ruan, C., Zhang, D., & Pan, X. (2024). Polysaccharide preferred minority-dominant community assembly and exoenzyme enrichment in transparent exopolymer particles: Implication for global carbon cycle in water. *Science of The Total Environment*, *914*, 169976. https://doi.org/10.1016/j.scitotenv.2024.169976

[13] Zhao, C., Xun, F., Li, B., Han, X., Liu, H., Du, Y., ... & Xing, P. (2024). The dual roles of dissimilatory iron reduction in the carbon cycle: The "iron mesh" effect can increase inorganic carbon sequestration. *Global Change Biology*, *30*(3), e17239. https://doi.org/10.1111/gcb.17239

[14] Tang, Z., Wang, D., Tian, X., Bi, X., Zhou, Z., Luo, F., Ning, R., & Li, J. (2024). Exploring the factors influencing the carbon sink function of coastal wetlands in the Yellow River Delta. *Scientific Reports, 14*(1), 28938. https://doi.org/10.1038/s41598-024-80186-8

[15] Mitsch, W. J., Bernal, B., Nahlik, A. M., Mander, Ü., Zhang, L., Anderson, C. J., ... & Brix, H. (2013). Wetlands, carbon, and climate change. *Landscape* ecology, *28*(4), 583-597. https://doi.org/10.1007/s10980-012-9758-8

[16] Guiry, E. J., Orchard, T. J., Needs-Howarth, S., & Szpak, P. (2022). Freshwater wetland–driven variation in sulfur isotope compositions: Implications for human paleodiet and ecological research. *Frontiers in Ecology and Evolution*, *10*, 953042. https://doi.org/10.3389/fevo.2022.953042

[17] Raturi, A., Raturi, A., & Singh, H. (2024). Climate change impacts on wetland ecosystem functioning with special reference to greenhouse gas emissions. In *Forests and Climate Change: Biological Perspectives on Impact, Adaptation, and Mitigation Strategies* (pp. 345-364). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-3905-9_18

[18] Xiao, D., Deng, L., Kim, D. G., Huang, C., & Tian, K. (2019). Carbon budgets of wetland ecosystems in China. *Global Change Biology*, *25*(6), 2061-2076. https://doi.org/10.1111/gcb.14621

[19] Yin, Y., Yang, R., Song, Z., Lu, Y., Zhang, Y., Zhang, L., Sun, M., & Li, X. (2024). Simulation of wetland carbon storage in coastal cities under the coupled framework of socio-economic and ecological sustainability: A case study of Dongying city. *Sustainable Cities and Society, 108*, 105481. https://doi.org/10.1016/j.scs.2024.105481