

The Role of Freshwater Bodies in Carbon Cycling and Climate Change Mitigation

^{1*} João Silva, Portuguese Institute for Atlantic Innovation Research, Lisbon, Portugal.

² Inês Costa, Portuguese Institute for Atlantic Innovation Research, Lisbon, Portugal.

Abstract: The various freshwater bodies, comprising rivers, lakes, wetlands, and reservoirs, are very dynamic yet undervalued parts of the global carbon cycle. Despite occupying less than one percent of the total surface area of the Earth, they play a very significant role in governing terrestrial carbon release into the oceans, controlling greenhouse gas fluxes, and modifying local climate feedbacks. The present work aims to understand the role of freshwater systems in the carbon cycle, focusing specifically on DOC, DIC, and POC at selected freshwater bodies in the Western Ghats and Deccan Plateau regions of South India. Samples were collected seasonally from five different freshwater body types. Data on water chemistry, carbon flux parameters, and pCO₂ levels was obtained over a period of one year. This shows that the highest carbon concentration and $8.7 \pm 1.1 \text{ mg C L}^{-1}$ and CO₂ evasion rates occur during the monsoon season, where DOC concentration attains the value $8.7 \pm 1.1 \text{ mg C L}^{-1}$ and CO₂ flux is estimated at $22.6 \pm 3.4 \text{ mmol m}^{-2} \text{ d}^{-1}$. Human activities such as agricultural and industrial effluents have greatly increased carbon content in the waters. Wetlands were identified to have the highest carbon sequestration capacity, which ranged from 0.22 to 0.45 Tg C yr⁻¹. Various climate mitigation measures were evaluated in terms of their climate benefits.

Keywords: Freshwater Carbon Cycling; Dissolved Organic Carbon; Greenhouse Gas Emissions; Climate Change Mitigation; Aquatic Biogeochemistry; Western Ghats Waterbodies; Carbon Sequestration.

(Submitted: June 28, 2025; Revised: July 28, 2025; Accepted: August 19, 2025; Published: September 30, 2025)

I. Introduction

The global carbon cycle is a dynamic system of flows between the atmosphere, biosphere, lithosphere, and hydrosphere. Despite the extensive research and consideration of terrestrial and oceanic carbon sinks, freshwater systems are still poorly understood despite their importance in the carbon cycle (Canuel et al., 2012). Freshwater ecosystems are involved in the fluxes, conversions, and fixation of enormous amounts of carbon transported from land. Recent studies provide increasing support for the role of inland waters as sources of atmospheric CO₂ and CH₄ and pathways of organic and inorganic carbon towards the oceans (Butman et al., 2016; Ward et al., 2017). Climate change feedbacks associated with freshwater carbon dynamics are becoming one of the biggest research gaps in the understanding of climate change issues that has not yet been adequately covered by the current national inventories or mitigation policies (Friedlingstein, 2015).

Human impacts on freshwater biogeochemistry over the last hundred years have been profound. Changes in land use, increases in agriculture production, urbanization, and industrialization have all led to increased nutrient loading, changes in flow regime, and greater input of organic materials to freshwater ecosystems (Sharma, 2024; Mukherjee et al., 2023; Lake et al., 2000). In addition, these anthropogenic changes have been exacerbated by climate change that alters the rainfall patterns, temperature, and extreme hydrological events, affecting the ability of freshwater ecosystems to modulate carbon flows (Woodward et al., 2010; Allan et al., 2020). The interactions between macronutrients including carbon, nitrogen, and phosphorus within aquatic ecosystems are highly interlinked, and any disturbance in one system will have a downstream effect on other systems (Jarvie et al., 2012; Whitehead & Crossman, 2012). While there is increasing awareness about the importance of the role of freshwater bodies as biogeochemical reactors and not just pipes, there is very little research done in the tropical and subtropical ecosystems (Roland et al., 2012).

In order to bridge the gaps identified above, the current paper seeks to look at the contribution made by freshwater systems in carbon cycle processes and carbon dioxide reduction with respect to climate change

mitigation using waterbodies within the Western Ghats and plateau regions of South India as the main region under consideration. In the process, the following three major points will be highlighted: (i) measurement of carbon flux parameters within diverse fresh water typologies throughout the year; (ii) influence of anthropogenic activities on carbon dynamics; and (iii) nature-based solutions for carbon mitigation.

The structure of the paper is set out below: Section 1 is the introduction. Section 2 is the review of literature. Section 3 outlines the study area and the methodology used. Section 4 contains findings while Section 5 is the discussion and conclusions.

II. Literature Survey

Freshwater environments act as active processors and transformers of carbon rather than as mere pipelines. Canuel et al. (Canuel et al., 2012) showed that the interface between land and ocean, which is controlled mainly by riverine inputs and estuaries, has a key role in controlling the export of organic carbon. This work pointed out the fact that the terrestrial organic matter would undergo decomposition, photochemical oxidation, and flocculation prior to reaching coastal areas while traveling through freshwater environments. Later, Ward et al. (Ward et al., 2017), using the concept of aquatic continuum, showed that carbon transport is highly variable and controlled by the nature of watershed, processing in the water column by microbes, and the patterns of land use.

The linkage between the carbon cycle and the cycles of nitrogen and phosphorus through biogeochemistry has been identified as another vital area of study for fresh water carbon. As Jarvie et al., (2012) and Whitehead and Crossman (2012) have pointed out, the process of nutrient enrichment through agricultural runoff affects the stoichiometry of carbon processing, leading to enhanced algal growth, increased concentrations of dissolved organic carbon and, finally, increased rates of CO₂ evasion. The role of nutrient loading, particularly nitrogen, in conjunction with carbon cycling, resulting in feedback impacts on climate was further elucidated by Suddick et al., (2013). Woodward et al. (2010) have demonstrated that the effect of climate change on microorganisms' metabolism as influenced by temperature leads to increased rate of decomposition of organic carbon and emission of greenhouse gases. The implication derived from all these studies is that nutrients and carbon cycles need to be addressed collectively.

The involvement of particular types of freshwater ecosystems, such as wetlands, artificial lakes, and tropical rivers, in carbon turnover processes was discussed widely within recent years. For instance, Roland et al., (2012) proved that inland waters in Brazil could be identified as major sources of both CO₂ and CH₄, with the emissions being a result of hot weather, presence of organic carbon matter, and land-use changes in nearby watersheds. The significance of carbon dynamics in freshwater ecosystems in the United States is described in the work conducted by Butman et al. (2016), indicating that aquatic carbon cycle in the USA cannot be ignored when estimating carbon turnover on land since the current models underrepresent carbon turnover in inland waters. Furthermore, Reitsema et al. (2018) pointed out the importance of the impact made by freshwater macrophytes on DOC, considering these ecosystems as regulators of carbon matter and its availability. Sharma (2024) analyzed Indian rivers focusing on the contribution made by anthropogenic activity.

Freshwater ecosystem-based approaches for mitigating climate change have attracted considerable attention as supplementary means alongside traditional terrestrial ones. Schmitz & Sylvén (2023) made a very strong case for using conservation of wildlife and ecosystems as ways of improving carbon regulation within natural systems because biodiversity loss threatens such regulation within aquatic ecosystems. Singh et al. (Singh et al., 2023) investigated the possibilities of sequestering carbon through the biomass of aquatic plants, thus proving its viability as a nature-based solution to climate change. Lake et al., (2000) and Moss (2014) both stressed that conservation and restoration of freshwater ecosystems would result in multiple benefits related to carbon storage and climate mitigation besides improved water quality. In particular, Sarkar & Borah (2018) identified floodplain wetlands as key sources of carbon sinks in India, while

Abubakar & Dano (2020) took this approach further by emphasizing the contribution of freshwater ecosystem management within urban centers to climate change mitigation.

Conceptual Framework

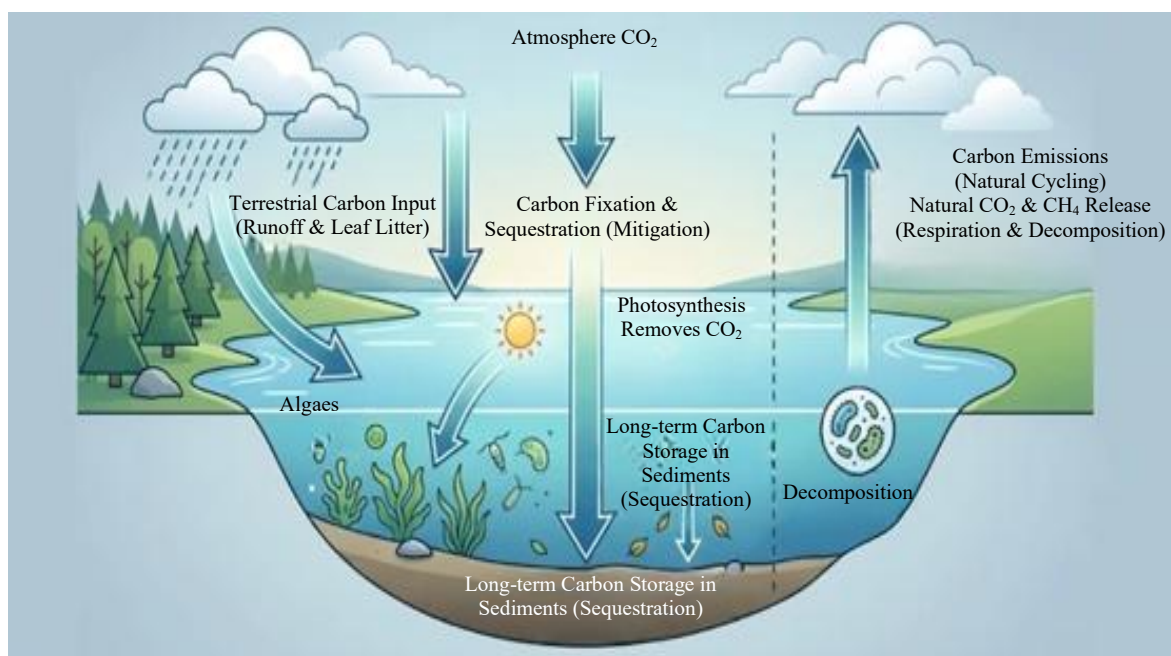


Figure 1: Carbon Cycling and Sequestration in Aquatic Ecosystems

Figure 1 below represents the natural carbon cycle within aquatic ecosystems. Carbon dioxide from the atmosphere is absorbed through photosynthesis by aquatic plants such as algae and then stored in sediments through sequestration, before finally being released through decomposition and respiration.

III. Materials and Methods

Study Area Description

The survey was carried out in five freshwater systems representing different types that are found in the Western Ghats biodiversity hotspot and the Deccan plateau region in southern India at elevations of 400 meters to 2,400 meters above sea level. These systems include: the Cauvery River (lotic system with a basin size of 81,155 square kilometers); Ooty Lake (lentic system with a surface area of 2.4 square kilometers); Pykara Reservoir (reservoir system with a surface area of 14.2 square kilometers); Bhavani River (tributary system with a basin size of 6,180 square kilometers); and Mukurthi Wetlands (montane wetland with a surface area of 78.5 square kilometers). The study region has a humid subtropical or tropical climate, with a strong southwest monsoon during June to September, when about 70 percent of the annual precipitation occurs. Different biogeochemical conditions prevail in the studied sites due to elevation and land use gradients. The sites chosen include different catchment land uses (forests, agriculture, and urban), water residence time, and hydrology. Table 1 gives details of each study area.

Table 1: Summary Characteristics of the Five Selected Freshwater Study Areas in South India

Study Area	Type of Waterbody	Location	Area (km ²)	Primary Carbon Pool Studied
Cauvery River Basin	River	South India	81,155	Dissolved Inorganic Carbon (DIC)
Ooty Lake	Lake (Lentic)	Tamil Nadu, India	2.4	Dissolved Organic Carbon (DOC)
Pykara Reservoir	Reservoir	Tamil Nadu, India	14.2	Particulate Organic Carbon (POC)
Bhavani River	River/Tributary	Western Ghats, India	6,180	CO ₂ Evasion & DIC Flux
Mukurthi Wetland	Montane Wetland	Nilgiris, Tamil Nadu	78.5	Sediment Carbon Storage

Sampling and Laboratory Methods

Monthly sampling of water was conducted at each site during one year of sampling, stratified into four seasons, namely, pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–December), and winter (January–February). Water samples were taken at standardized depth intervals using the Van Dorn water sampler at three replicate stations at each site. In-situ measurements of water temperature, pH, dissolved oxygen, and electrical conductivity were made using a calibrated multiparameter water quality probe (YSI Pro Plus). DOC sampling was conducted by immediate filtering through pre-combusted 0.7 µm glass fiber filters (Whatman GF/F) and preserving the samples in amber glass vials at 4°C until analysis. Concentrations of DOC and DIC were analyzed by a total organic carbon analyzer (Shimadzu TOC-L series), calibration with certified reference materials. POC concentration was estimated gravimetrically after filtering water samples on pre-weighted GF/F filters dried at 60°C for 24 hours. Isotope analysis of carbon ($\delta^{13}\text{C}$) was made using an isotope ratio mass spectrometer to differentiate between allochthonous and autochthonous sources of carbon. pCO₂ was measured with a portable infrared CO₂ analyzer (LI-COR LI-820) with headspace equilibration. Chemical analyses of samples were done in triplicates, including procedural blanks, spiked recovery and duplicate analyses.

Carbon Flux Estimation and Statistical Analysis

The air to water exchange flux of CO₂ was estimated based on the thin boundary layer approach as follows: $F = k \times \alpha \times (p \text{ CO}_2 \text{ water} - p \text{ CO}_2 \text{ air})$. In this formula, k represents the gas exchange coefficient which was estimated from the wind speed measurements using empirical relations, while α represents the solubility coefficient of CO₂ which was obtained from water temperature and salinity. The wind speed was measured using the nearest India Meteorological Department station. The yearly budgets of the carbon flux were estimated based on integration of seasonal flux estimates, weighted according to the time duration of each season. Data on land use for characterization of catchment areas were acquired through the interpretation of Landsat 8 satellite images at a spatial resolution of 30m and processed using supervised classification based on the maximum likelihood algorithm in QGIS 3.22. Spatial analysis was done to determine the percentage area covered by forests, agriculture, and urbanization within a 10km radius of each of the study sites. Statistical analysis and graphing were done using Python 3.10+. Analysis of variance (ANOVA), followed by Tukey post-hoc test was done to analyze significant differences in carbon parameters between seasons and sites. Pearson's correlation coefficient analysis was used for finding correlations between concentrations of carbons and environmental factors (temperature, pH, and discharge). Regression analyses were conducted to determine linear equations to estimate DOC and DIC using catchment land use variables. Mean values $\pm$ standard deviations are presented in all cases, and $p < 0.05$ is considered statistically significant.

IV. Results

Seasonal Variation in Carbon Parameters

Seasonal variation was significant for all the carbon parameters analyzed during the study period at the five sampling locations ($p < 0.001$ by ANOVA). The highest DOC concentration was recorded during the monsoon ($8.7 \pm 1.1 \text{ mg C L}^{-1}$), while the lowest occurred during the winter ($2.8 \pm 0.3 \text{ mg C L}^{-1}$), resulting in a seasonal variation of three times. Similar to DOC concentration, DIC had a lesser seasonal variation; it reached its maximum during the monsoon ($18.1 \pm 2.3 \text{ mg C L}^{-1}$). The largest seasonal increase in POC concentration occurred during the monsoon, increasing from $0.9 \pm 0.1 \text{ mg C L}^{-1}$. The levels of pCO_2 varied between $580 \pm 41 \text{ } \mu\text{atm}$ (wintertime) and $1,420 \pm 189 \text{ } \mu\text{atm}$ (monsoon time), consistently being higher than the atmospheric equilibrium level. The CO_2 flux was recorded to be between $6.9 \pm 0.9 \text{ mmol m}^{-2} \text{ d}^{-1}$ (winter) and $22.6 \pm 3.4 \text{ mmol m}^{-2} \text{ d}^{-1}$ (monsoon). Strong negative relationship was detected between pH and pCO_2 levels ($r = -0.82$, $p < 0.001$) and strong positive relationship between water temperature and DOC levels during non-monsoon seasons ($r = 0.74$, $p < 0.01$). Seasonal carbon balance is shown in figure 2.

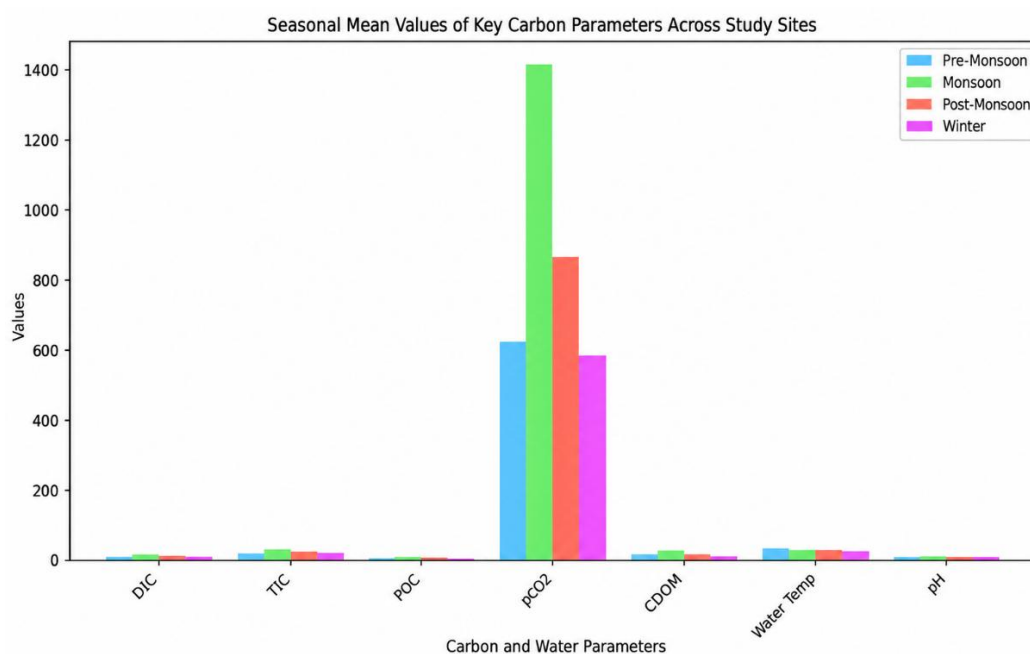


Figure 2: Seasonal Mean Values of Key Carbon Parameters Across Study Sites

Site-Specific Carbon Dynamics

Amongst the five sampling sites, Mukurthi Wetland was observed to contain the highest amount of carbon stored in sediment ($4.2 \pm 0.6 \text{ kg C m}^{-2}$) as well as the lowest average of pCO_2 ($680 \pm 72 \text{ } \mu\text{atm}$). On the other hand, Pykara Reservoir had the highest average value of pCO_2 ($1,180 \pm 210 \text{ } \mu\text{atm}$) as well as the highest flux of CO_2 evasion ($18.4 \pm 2.8 \text{ mmol m}^{-2} \text{ d}^{-1}$). This indicated increased organic matter decomposition in stratified waters. The Cauvery River had moderately high levels of carbon concentration but there was a clear pulse of DOC exports during monsoon onset due to flushing of accumulated organic matter. In case of Bhavani River, higher values of DOC were seen after the monsoon season ($6.8 \pm 0.9 \text{ mg C L}^{-1}$). The lake Ooty had the lowest POC concentration (mean annual value: $1.2 \pm 0.3 \text{ mg C L}^{-1}$) but had a high share of autochthonous carbon based on $\delta^{13}\text{C}$ values ($-24.1 \pm 1.3\text{‰}$) relative to river systems which were dominated by allochthonous contribution ($\delta^{13}\text{C}$ values $-27.6 \pm 1.8\text{‰}$). Results from land-use regression model revealed negative relationship between percentage forest cover and DOC export ($R^2 = 0.71$, $p < 0.01$), whereas there was positive relationship with cultivation cover ($R^2 = 0.68$, $p < 0.01$).

Mitigation Strategy Assessment

A total of six nature-based mitigation options were analyzed based on their carbon sequestration potentials and feasibilities. The highest carbon sequestration potential from wetlands was estimated at 0.22–0.45 Tg C yr⁻¹, with riparian reforestation ranking second at 0.12–0.28 Tg C yr⁻¹ and agroforestry buffer zone third at 0.10–0.22 Tg C yr⁻¹. Restoration of macrophytes had significant sequestration potential at 0.08–0.19 Tg C yr⁻¹ but led to the reduction of DOC bioavailability. Wastewater treatment of urban runoff had the least but meaningful potential of sequestration, which is 0.03–0.09 Tg C yr⁻¹. It was revealed that the mitigation of agricultural runoff can effectively reduce not only nutrient loading but also the evasion of CO₂ emissions, resulting in an average 31% reduction in DOC concentration during the monsoon season within the experimental buffers in table 2.

Table 2: Nature-Based Mitigation Strategies, Mechanisms, and Estimated Carbon Sequestration Potential

Mitigation Strategy	Mechanism	Estimated Carbon Sequestration Potential (Tg C yr⁻¹)	Implementation Feasibility
Riparian Reforestation	Increases Allochthonous Carbon Input and Bank Stabilization	0.12 – 0.28	High
Macrophyte Restoration	Enhanced in-Situ Organic Carbon Production and Sediment Burial	0.08 – 0.19	Moderate
Wetland Conservation	Long-Term Sediment Carbon Storage and CH ₄ Flux Reduction	0.22 – 0.45	High
Reducing Agricultural Runoff	Lowers Nutrient Loading, Reduces Algal Bloom and CO ₂ Evasion	0.05 – 0.14	Moderate
Urban Wastewater Treatment	Reduces Labile DOC and Microbial Respiration in Rivers	0.03 – 0.09	Low–Moderate
Agroforestry Buffer Zones	Reduces Erosion, Increases POC Burial in Downstream Systems	0.10 – 0.22	High

V. Discussion

The results from the study show that the freshwater systems in the Western Ghats and adjacent areas are very much a part of the carbon cycle of the area as they are seasonally dynamic. The high DOC concentrations (8.7 ± 1.1 mg C L⁻¹), DIC (18.1 ± 2.3 mg C L⁻¹), and CO₂ emissions (22.6 ± 3.4 mmol m⁻² d⁻¹) in relation to the monsoon period prove that the hydrology dynamics are the major forces behind carbon dynamics within the tropical freshwater ecosystems. This is in agreement with the global aquatic carbon continuum theory presented by Ward et al. (Ward et al., 2017) and the seasonal carbon export process described by Canuel et al. (Canuel et al., 2012) within the land-sea interface. The supersaturation levels recorded in the freshwater ecosystems for both sites in the study region for all seasons suggest that the studied region acts mainly as a source of CO₂ within the atmosphere, a conclusion similar to that drawn for other tropical ecosystems in Brazil and the USA (Butman et al., 2016; Roland et al., 2012).

The significant role of land use on carbon dynamics is evident from the positive relationship between cultivated area and DOC export ($R^2 = 0.68$, $p < 0.01$), while there exists an inverse relationship between forest cover and DOC export ($R^2 = 0.71$, $p < 0.01$). This suggests that the freshwater carbon cycle may be highly sensitive to the anthropogenic impacts of changing land use. Indeed, these observations are

supported by earlier investigations by Sharma (Sharma, 2024) and Mukherjee et al. (Mukherjee et al., 2023) emphasizing that intensified agriculture and urban effluents tend to increase the carbon load of rivers. The high concentration of DOC in the Bhavani River following the monsoon season resulting from rice paddies drainage exemplifies the mechanism for how anthropogenic land use can impact carbon ratios in aquatic ecosystems as per the macronutrient coupling hypothesis proposed by Jarvie et al. (Jarvie et al., 2012). On the contrary, the presence of reservoirs like Pykara where there are high levels of pCO_2 and CO_2 flux due to organic matter degradation and thermal stratification.

The outcomes of the freshwater carbon sequestration analysis reveal wetlands protection and riparian trees planting as the most successful methods of climate change mitigation in freshwater systems. The sequestration potential estimation of $0.22\text{--}0.45\text{ Tg C yr}^{-1}$ is consistent with estimates worldwide of montane and tropical wetlands sequestration potential and proves the outcomes of Sarkar and Borah (Sarkar & Borah, 2018) about undervalued mitigation potential of Indian floodplains. The efficiency of DOC decrease from monsoon agricultural buffer areas supports the conclusions of Allan et al. (Allan et al., 2020) and Reitsema et al. (Reitsema et al., 2018) on the necessity of incorporating the aspects of both carbon and nutrients management in land-water management practices. Relatively small yet still important amount of urban wastewater sequestration proves the importance of urban water management for rapid development of Indian cities (Abubakar & Dano, 2020). Finally, it should be concluded that the analysis of carbon sequestration by freshwaters reveals an important aspect of the problem that needs to be considered.

VI. Conclusion

With respect to field evidence, the current document stresses that seasonality is one of the aspects concerning freshwater ecosystems within the Western Ghats and the Deccan Plateau of South India being CO_2 emitters. Carbon sequestration capabilities in those ecosystems are observed predominantly in montane wetlands and riparian forest strips. The monsoon period was noted to play a crucial role for mobilization, as it brought the highest amounts of DOC, DIC, POC, and CO_2 fluxes because of enhanced flushing of terrestrial OM and connectivity. Anthropogenically induced land use alterations were identified as essential factors determining carbon loads; cultivated catchment ecosystems demonstrated higher carbon emissions than forests. Among the proposed solutions for mitigating climate change, wetland conservation ($0.22\text{--}0.45\text{ Tg C yr}^{-1}$), riparian restoration ($0.12\text{--}0.28\text{ Tg C yr}^{-1}$), and agroforestry buffers ($0.10\text{--}0.22\text{ Tg C yr}^{-1}$) stood out. Conclusions. This study's results have immediate bearing on the incorporation of the dynamics of freshwater carbon into India's nationally determined contributions and state-level climate change policies. More research is required in the continuous estimation of fluxes of greenhouse gases from tropical freshwater systems through eddy covariance and automated sensors. Process-oriented modeling of the carbon cycle in tropical freshwaters based on field observations would better predict the effect of changes in climate and land use on freshwater carbon fluxes. The scope of this study can be broadened by investigating the fluxes of CH_4 , the microbial communities, and isotopic signatures of freshwater carbon dynamics.

Declaration Statements

Conflict of Interest: The authors declare no conflict of interest.

Funding: This research received no external funding.

Dataset Description: The dataset generated and analyzed during this study is available from the corresponding author upon reasonable request.

References

- [1] Canuel, E. A., Cammer, S. S., McIntosh, H. A., & Pondell, C. R. (2012). Climate change impacts on the organic carbon cycle at the land-ocean interface. *Annual Review of Earth and Planetary Sciences*, 40(1), 685–711. <https://doi.org/10.1146/annurev-earth-042711-105511>
- [2] Friedlingstein, P. (2015). Carbon cycle feedbacks and future climate change. *Philosophical Transactions of the Royal Society A*, 373(2054). <https://doi.org/10.1098/rsta.2014.0421>
- [3] Sharma, D. (2024). Role of rivers in the carbon cycle and the impact of anthropogenic activities. In *Rivers of India: Past, Present and Future* (pp. 173–196). Springer. https://doi.org/10.1007/978-3-031-49163-4_10
- [4] Jarvie, H. P., Jickells, T. D., Skeffington, R. A., & Withers, P. J. A. (2012). Climate change and coupling of macronutrient cycles along the atmospheric, terrestrial, freshwater and estuarine continuum. *Science of the Total Environment*, 434, 252–258. <https://doi.org/10.1016/j.scitotenv.2012.07.051>
- [5] Schmitz, O. J., & Sylvén, M. (2023). Animating the carbon cycle: how wildlife conservation can be a key to mitigate climate change. *Environment: Science and Policy for Sustainable Development*, 65(3), 5–17. <https://doi.org/10.1080/00139157.2023.2180269>
- [6] Mukherjee, S., Rizvi, S. S., Biswas, G., Paswan, A. K., Vaiphei, S. P., Warsi, T., & Mitran, T. (2023). Aquatic ecosystems under influence of climate change and anthropogenic activities. *Hydrogeochemistry of Aquatic Ecosystems*, 307–331. <https://doi.org/10.1002/9781119870562.ch14>
- [7] Butman, D., Stackpoole, S., Stets, E., McDonald, C. P., Clow, D. W., & Striegl, R. G. (2016). Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting. *Proceedings of the National Academy of Sciences*, 113(1), 58–63. <https://doi.org/10.1073/pnas.1512651112>
- [8] Woodward, G., Perkins, D. M., & Brown, L. E. (2010). Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B*, 365(1549), 2093–2106. <https://doi.org/10.1098/rstb.2010.0055>
- [9] Roland, F., Huszar, V. L. M., Farjalla, V. F., Enrich-Prast, A., Amado, A. M., & Ometto, J. P. H. B. (2012). Climate change in Brazil: perspective on the biogeochemistry of inland waters. *Brazilian Journal of Biology*, 72(3 suppl), 709–722. <https://doi.org/10.1590/S1519-69842012000400009>
- [10] Reitsema, R. E., Meire, P., & Schoelynck, J. (2018). The future of freshwater macrophytes in a changing world. *Frontiers in Plant Science*, 9, 629. <https://doi.org/10.3389/fpls.2018.00629>
- [11] Lake, P. S., Palmer, M. A., Biro, P., Cole, J., Covich, A. P., Dahm, C., et al. (2000). Global change and the biodiversity of freshwater ecosystems. *BioScience*, 50(12), 1099–1107. [https://doi.org/10.1641/0006-3568\(2000\)050\[1099:GCATBO\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2000)050[1099:GCATBO]2.0.CO;2)
- [12] Moss, B. (2014). Fresh waters, climate change and UK nature conservation. *Freshwater Reviews*, 7(1), 25–75. <https://doi.org/10.1608/FRJ-7.1.789>
- [13] Ward, N. D., Bianchi, T. S., Medeiros, P. M., Seidel, M., Richey, J. E., Keil, R. G., & Sawakuchi, H. O. (2017). Where carbon goes when water flows. *Frontiers in Marine Science*, 4, 7. <https://doi.org/10.3389/fmars.2017.00007>
- [14] Allan, R. P., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. J., et al. (2020). Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, 1472(1), 49–75. <https://doi.org/10.1111/nyas.14337>
- [15] Sarkar, U. K., & Borah, B. C. (2018). Flood plain wetland fisheries of India: with special reference to impact of climate change. *Wetlands Ecology and Management*, 26(1), 1–15. <https://doi.org/10.1007/s11273-017-9559-6>
- [16] Singh, P., Sharma, S., & Dhanorkar, M. (2023). Aquatic plant biomass-derived porous carbon: biomaterials for sustainable waste management and climate change mitigation. *International Journal of Environmental Science and Technology*, 20(11), 12955–12970. <https://doi.org/10.1007/s13762-022-04601-1>

- [17] Abubakar, I. R., & Dano, U. L. (2020). Sustainable urban planning strategies for mitigating climate change in Saudi Arabia. *Environment, Development and Sustainability*, 22(6), 5129–5152. <https://doi.org/10.1007/s10668-019-00417-1>
- [18] Whitehead, P. G., & Crossman, J. (2012). Macronutrient cycles and climate change: key science areas and an international perspective. *Science of the Total Environment*, 434, 13–17. <https://doi.org/10.1016/j.scitotenv.2011.08.046>
- [19] Suddick, E. C., Whitney, P., Townsend, A. R., & Davidson, E. A. (2013). The role of nitrogen in climate change and the impacts of nitrogen-climate interactions in the United States. *Biogeochemistry*, 114(1), 1–10. <https://doi.org/10.1007/s10533-012-9795-z>