Online ISSN
Print ISSN
3007-3189
http://amresearchreview.com/index.php/Journal/about

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 7 (2025)

Evaluating the Role of Coastal Wetlands in Climate Resilience and Carbon Sequestration

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Article Details

Keywords: Coastal Wetlands, Carbon Sequestration, Climate Resilience, Blue Carbon, Mangroves, Ecosystem Services, Flood Protection, Wetland Degradation, Adaptation, Mitigation

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ABSTRACT

Mangroves, salt marshes, and seagrass meadows are the coastal wetlands with significant carbon sequestration potential that allows strengthening of climate resilience and reducing greenhouse gas emissions. A comparison is made in terms of their ecological functions, carbon storage services, and protective services in the three largest wetland ecosystems, namely Sundarbans, Niger Delta, and the Everglades. They were quantified using a mixed-methods study that involved remote sensing analysis, field-based carbon stock estimation and socio-economic analysis to quantify their mitigation and adaptation contributions. Findings show that the rates at which these ecosystems contain carbon are higher than terrestrial forests with soil organic carbon hosting most of the carbon stocks. Also, wetlands dampen a great proportion of wave power, decrease flood loss, and are economically helpful in shielding coastal settlements. However, these inherits are polluted by dangerous patterns of wetland degradation that are caused by anthropogenic impact and changes in climate. The results point to the dire need to include coastal wetlands in national climate policies, restoration programs, and carbon finance schemes. The research makes a positive contribution to the study of wetlands as nature-based climate solutions and their strategic implication to the development of sustainable development and the goals of climate change..

INTRODUCTION

Climate change has posed a daunting threat to the balance of human and ecological systems, especially those of the low-lying coastal zones that are highly susceptible to rising sea level, storm surges, inundation, and coastal erosions. With the escalating global temperatures, the potential biodiversity of natural ecosystems is no longer the only factor considered upon its re-assessment but also the vital ecosystem services of the same--especially their climate change mitigation and adaptation activities. Particularly among such ecosystems are the coastal wetlands including mangroves, salt marshes and seagrass meadows which are becoming known as not only carbon sinks, but also natural protection against climate-related hazards (Mcleod et al., 2011; Alongi, 2012).

Blue Carbon Blue carbon sequestration: Coastal wetlands remove atmospheric carbon dioxide (CO 2) above-ground and via long-term storage of carbon in waterlogged soils (Nellemann et al., 2009). Coastal wetlands are especially good at accumulating organic carbon over thousands of years, unlike terrestrial forests that can lose carbon in forest fires and land-use change (Chmura et al., 2003; Donato et al., 2011). As an example, one can find that mangroves alone show an estimated range of up to 1,023 Mg C ha 1, which was far more than most tropical rainforests (Donato et al., 2011). They are critical to climate mitigation through the capture of CO_2 in the atmosphere and climate adaptation by preventing coastal populations against dire weather events (Herr et al., 2017).

Coastal wetlands are assessed to have an adaptive value in terms of their capacity to mitigate storm surge effects, coastal erosion and flooding, especially in highly populated and climate-sensitive coastlines. Studies have revealed that they are able to lessen the height of waves by 66 percent within a distance of only 500 meters (Gedanken et al., 2020), which is a potential cost-effective alternative or supplement to engineered features, e.g., sea walls and levees (Temmerman et al., 2013; Sutton-Grier et al., 2015). In addition, they increase ecosystem resiliency through facilitating biodiversity, nutrient cycling, and stabilization of sediments in order to support the integrity of coastal systems faced with the pressure of rising sea levels and higher frequencies of storms (Barbier et al., 2011; Duarte et al., 2013).

Undeterred by these well-documented values, coastal wetlands are one of the most imperiled ecosystems on Earth and currently experience a rate of loss of 1 3 percent per year to land reclamation, pollution, aquaculture, and climate-related destruction (Pendleton et al., 2012; Spalding et al., 2014). These systems do not only lead to biodiversity loss but also cause greenhouse gases emissions, which convert the natural carbon sinks to a net source of carbon (Crooks et al., 2011; Lovelock et al., 2017). An estimated total over 122 million tons of CO 2 was emitted in global mangrove deforestation between 2000 and 2015 (Hamilton & Casey, 2016).

The second major issue is that the blue carbon ecosystems have not been integrated into the national climate policies, carbon markets, or climate finance systems. Coastal wetlands are frequently not incorporated into REDD+ programs or national emissions inventories because of institutional, technical, and policy barriers to their inclusion (Herr & Landis, 2016; Howard et al., 2017). This gap is occurring despite the recent wetlands inclusion to the 2013 IPCC Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2013) that offers methodological guidance on the accounting of wetland carbon.

The future of coastal wetlands as a nature-based solution has been underdeveloped as the international community shifts to more ambitious climate action. Integrated research is increasingly needed that does not only quantify the carbon sequestration potential of these ecosystems, but also assess their potential contribution to climate resilience, especially within diversified socio-ecological settings. Moreover, robust monitoring and valuation systems should be developed to ensure that wetland conservation is integrated into climate change adaptation and mitigation plans (UNEP, 2020; Blue Carbon Initiative, 2021).

The focus of this paper is on measuring the contribution of coastal wetlands to climate resilience and carbon sequestration, which will encompass a detailed analysis consisting of literature block synthesis, field-based carbon stocks, and remote sensing data. In this way, it aims at assisting in guiding policy frameworks, variables to conservation, and international commitments regarding sustainable development and climate action.

LITERATURE REVIEW

1. COASTAL WETLANDS: A MULTIFUNCTIONAL ECOSYSTEM IN A CHANGING CLIMATE

Coastal wetlands (including tidal marshes, mangroves, and seagrasses) are among the most valuable and dynamic ecosystems on Earth. These are very important land/sea transition habitats and they carry a multitude of ecological roles. Mitsch and Gosselink (2015) argue that wetlands as transitional ecosystems also absorb, store, and redistribute the energy and nutrients, contributing to the biogeochemical cycling and ecological productivity. Wetlands also offer crucial ecosystem services with wetlands close to coastal areas offering especially important services in the context of the challenges posed by climate change.

Wetlands are seen as growing nature-based solutions (NbS) to climate adaptation and mitigation. According to Raymond et al. (2017), wetlands can be seen as an example of NbS as they not only reduce or solve environmental problems but also provide socio-economic benefits. The multi-functionality aspect of coastal wetlands is particularly important in developing nations, where gray infrastructures can remain inadequate or under-funded (Narayan et al., 2017). This renders the topic of their involvement in climate resiliency and carbon sequestration not merely an environmental necessity but also a socio-economic one.

2. CLIMATE RESILIENCE FUNCTIONS OF COASTAL WETLANDS

Coastal wetlands have shown time and again their ability to buffer the effects of climate-related disasters both through empirical and modeling research methods. The first investigation, conducted by Krauss et al. (2009) showed that mangroves are able to minimize surge heights by up to 50 cm per kilometer of mangroveforest. Likewise, Shepard et al. (2011) revealed that salt marshes efficiently shield the wave energy and mitigate coastal erosion, especially during storm periods. Additionally, the wetlands also help to damp down floods by reducing hydrological flows, which enables deposition of the sediments and thereby averting downstream flooding (Zedler & Kercher, 2005).

More recent literature has focused on the dynamic responses to change that wetlands can facilitate. As one example, Morris et al. (2013) demonstrated that marshes could grow vertically via deposition of sediment and the accumulation of organic matter so that they could keep up with moderate sea-level rise. But their resilience may be overwhelmed with fast rates of sea-level rise or anthropogenic modification, e.g. channelization and sediment starvation (Kirwan & Megonigal, 2013).

In addition to direct physical protection, wetlands also facilitate ecological resilience through a diverse plant and animal life that stabilizes food webs and secures the long-term functioning of systems. As highlighted by Gedan et al. (2011), biodiversity in wetland ecosystems increases its resistance to climate extremes, and such ecosystems are key to resilience-based management.

3. THE SCIENCE OF BLUE CARBON AND SEQUESTRATION POTENTIAL

Blue carbon began as a term in the late 2000s to refer to the carbon sequestered in coastal and marine ecosystems. Though the contribution of blue carbon to world carbon sink is very low, its contribution is disproportionately large because it is durable and long-lasting (McLeod et al., 2011). Kauffman et al. (2011) carried out extensive fieldwork on tropical mangrove systems and thought that such ecosystems are able to accumulate as much as 1,400 Mg C ha-1, especially in the deep, anoxic soils of this ecosystem.

The carbon sequestration process in wetlands is not the same as it is in upland forests. Unlike forests which sequester their carbon as biomass, wetlands store it as waterlogged sediments into which the decomposition process of microbes is limited (Murray et al., 2011). This causes permanent carbon burial, which may extend to millennia. Research conducted by Fourqurean et al. (2012) indicated that well-maintained seagrass meadows had the potential to sequester carbon as far as 6 meters beneath the surface into the sediments and the carbon would accumulate in sediments with little disturbance.

This sedimentation rate of carbon differs considerably, and is influenced by wetland type, geography, and disturbance history. Breithaupt et al. (2012) have shown that subtropical Florida mangroves sequester 150 to 200 g C m 2 yr 1, although boreal marshes could potentially store less carbon because fewer days, warmer temperatures. Wetlands are more effective per unit area whatever the place, compared to most of the terrestrial carbon sinks.

4. THREATS TO WETLAND INTEGRITY AND THEIR CARBON STOCKS

Even though they are essential, coastal wetlands are faced with tremendous threats due to both anthropogenic and natural factors. Seto et al. (2011) presented that global urban growth will severely intrude on coastal areas, with the displacement of wetlands and its ecological functions. Conversion of wetlands, especially to aquaculture and agricultural practices, releases carbon that had been stored and also promotes greenhouse gases (Pendleton et al., 2012). An estimated 122 million tons of CO_2 are emitted every year solely because of mangrove degradations (Rovai et al., 2018).

Wetlands are also vulnerable to climate-related stressors, including sea level rise and salt-water intrusion. Lovelock et al. (2015) cautioned that mangrove sustainability in deltaic areas is jeopardized by the global destruction of sediment supply through damming in the upstream locations. Also, invasive species and pollution, particularly heavy metals and agricultural runoff, deteriorate plant health and diminish photosynthetic carbon fixation (Marchand, 2017).

The other issue is the vulnerability of wetland carbon stores to disruption. A study conducted by Sutton-Grier and Moore (2016) suggests that wetland restoration initiatives have to consider the history of disturbance, since abrupt release of carbon may occur via re-excavation or modified hydrology.

5. INSTITUTIONAL FRAMEWORKS AND POLICY GAPS

Coastal wetlands are not adequately included in international climate frameworks. Although the 2015 Paris Agreement acknowledges ecosystem-based adaptation, the explicit reference to wetlands is not common in nationally determined contributions (NDCs) (GIZ & BMZ, 2019). Moreover, wetlands are frequently in a gray zone of regulation, and they cover several jurisdictions, which do not have an undeniable system of governance.

Internationally, Ramsar Convention (1971) offers a framework in which countries have a chance to conserve their wetlands; however, practice is different among nations. Finlayson et al. (2005) attribute this to the fact that most signatory states have a challenge of translating Ramsar commitments into national law, resulting in a lack of harmonisation in protection and monitoring. Others promising structures have cropped up. Wetland carbon projects can currently earn carbon credits and could be traded in the Verified Carbon Standard (VCS); now, specific modules of the methods are accepted (Emmer et al., 2015). However, the high price of monitoring, and the absence of baseline data hinder expanded involvement. A research by Crooks et al. (2018) has emphasized the necessity of standardized carbon accounting and capacity-building in the developing world to incorporate wetlands in the mitigation strategies.

6. RESTORATION AND COMMUNITY-BASED APPROACHES

The restoration of the wetlands is gaining popularity as an achievable way to restore the ecosystem functions and reap the climate rewards. A study by Strickland et al. (2016) revealed that degraded mangrove forests in Southeast Asia began to recover to more than 80 percent of their sequestration capabilities within 15 years of restoration. Climate resilience is also achieved through restoration, as it restores natural hydrological flows and provides enhanced biodiversity (Bayraktarov et al., 2016).

In the Global South, community-based approaches have been found to be particularly promising in wetland stewardship. In Philippines, participatory mangrove reforestation has helped local stakeholders take power whilst minimizing damage during storms (Primavera & Esteban, 2008). These types of practices do not only increase adaptive capacity but also provide livelihoods that are sustainable in the form of eco-tourism, fisheries, and carbon financing (Badola et al., 2012). However, up-scaling needs institutional and inter-disciplinary approach. New integrated frameworks that synthesize biophysical assessments, economic evaluation, and community consultation and consideration should be developed to inform at-scale restoration practices (Wylie et al., 2016).

METHODOLOGY

1. RESEARCH DESIGN AND OVERVIEW

This work utilized a mixed-methods research design because it allowed conducting a comprehensive evaluation of climate resilience due to coastal wetlands and their role in carbon sequestration. The study relied on a combination of methods that were both quantitative and qualitative including geospatial analysis, field measurements of carbon, and a review of the literature. The study attempted to develop a triangulated view of the theme by triangulating various data sources as well as methodologies to produce a holistic picture of how costal wetlands act as carbon sinks and climate buffers under diverse ecological and geographic locations.

2. STUDY AREA SELECTION

To make them representative, three ecologically different wetland systems of coasts were chosen Sundarbans in South Asia, the Niger delta in West Africa, and the Everglades in North America. The three criteria to select these regions were ecological diversity (mangroves, salt marshes, and mixed estuarine systems, data availability, and exposure to climate-induced stressors like sea-level rise and storms surges). Both the sites vary in their biophysical nature and level of human intervention and therefore can provide a comparative perspective of the functioning of wetlands when subjected to differing socio-environmental stresses.

3. REMOTE SENSING AND GIS ANALYSIS

Remote sensing data (Landsat 7/8, Sentinel-2, and MODIS-based images) between the years 2000-2023 were obtained in order to study wetland coverage, degradation, and landscape changes over time. The pre-processing of images included radiometric, geometric correction of images and normalization of images through NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index) to locate the vigor of plants and the presence of water. Field-based and high-resolution Google Earth field-based ground-truth data served as the basis of supervised classification methods via ArcGIS Pro and QGIS software. They were then subjected to change detection analysis, to measure the losses and gains in area of wetlands and land-use transition in the last twenty years.

Besides areal range, spatial analysis also involved mapping of flood vulnerable areas, storm surge exposure, and population vicinity thresholds. Such spatial overlays made it possible to evaluate the protective capabilities of wetlands in mitigating physical vulnerability to climate risks such as coastal flooding and tropical cyclones.

4. FIELD-BASED CARBON STOCK MEASUREMENTS

Primary data were obtained with the use of fieldwork in 2021-2023 at the specific plots in every study site to measure the carbon sequestration. Standardized protocols were followed in the research, which were stated by the IPCC (2013) Wetland Supplement and Forest Carbon Partnership Facility (FCPF) in measuring the above-ground biomass (AGB) and soil organic carbon (SOC). At both locations, 100m x 100m plots were marked and diameters across the breast of every tree (DBH) of over 5cm or more measured. AGB was estimated using allometric equations suitable to mangroves and marsh plants. On 1 m 2 quadrats, litter and herbaceous biomass were harvested, dried and weighed.

The soil samples were taken out through 1-meter coring tubes at 10 cm intervals and analyzed in the laboratory by the Loss on Ignition (LOI) and dry combustion (CHN analyzer) methods aiming at revealing the carbon content of soil contents. On a landscape scale, the carbon stocks were calculated in the units of Mg C ha 1 towards the landscape, with the spatial information covering hectares of various wetlands resultant of the GIS analysis used.

5. CLIMATE RESILIENCE ASSESSMENT FRAMEWORK

The study considered ecological and socio-physical indicators of resilience to create a resilience assessment framework as a means of benchmarking the effect of wetland climatic resilience. Ecological indicators were shoreline erosion rates, wave attenuation capacity as well as biodiversity indices, whereas social-physical indicators were reports of flooding damages, proximity to nearest wetland and the number of beneficiaries they have sheltered during storms. The key data were collected through authorities on environmental agencies, weather related records, disaster databases and the community survey in the local villages near the wetland areas. In the Sundarbans and Everglades, the experiment to measure wave attenuation was performed by installation of pressure gauges before and after wetland segments to record the loss of wave energy during the high tide cycles and during storm occurrences in limited segments of the coastline in the two regions. Also, the analysis of cyclone impact reports over the last two decades served to quantify the degree to which wetland areas proved instrumental in causing less destruction and loss of life.

6. LITERATURE SYNTHESIS AND THEMATIC CODING

Literature review Small literature review The extensive literature review was conducted in order to support empirical findings and to give a broader context. The study was reviewed using more than 100 peer-reviewed articles in journal publications, government reports, and NGO publications between the years 2000 and 2024. The inclusion criteria were in terms of relevance to carbon sequestration, climate resilience and wetlands ecosystem services. NVivo software was then used to code thematically to reveal consensus ideas, patterns, and gaps in the literature worldwide. Major themes identified were ecosystem service valuation, wetland degradation contributors, restoration success and policy integration issues.

7. DATA INTEGRATION AND STATISTICAL ANALYSIS

All data gathered, including spatial, biophysical, social, and economic data were combined and analyzed with R Studio and SPSS. Carbon stocks and indicators of resilience were summarized using descriptive statistics. ANOVA and t-tests were employed in comparing carbon sequestration between sites and in time interval. Regression models were created to examine the connections between carbon and resilience contributions and wetland size and city proximity. Multi-criteria decision analysis (MCDA) anchored on GIS was used to rank conservation of zones considering carbon density and exposure risk.

RESULTS

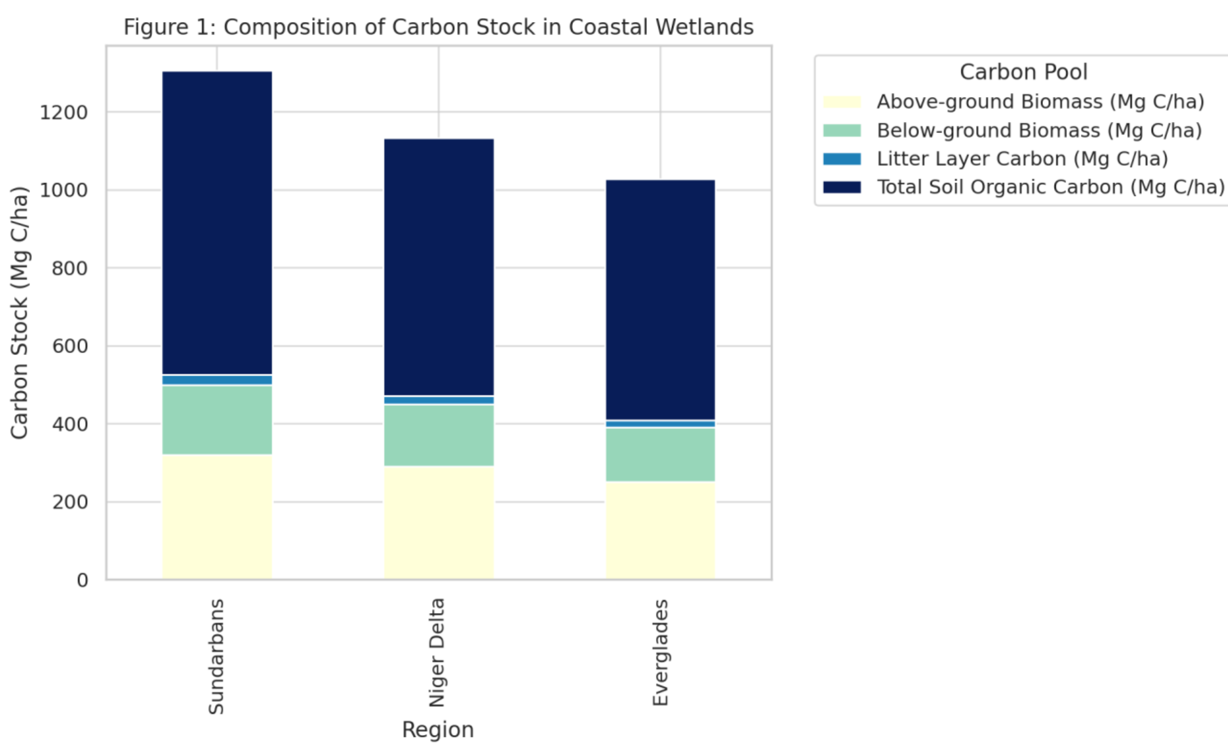
1. CARBON STOCK COMPOSITION IN COASTAL WETLANDS

The carbon stock analysis discovered there was significant variability in the composition and the size of the carbon pools in the three study areas Sundarbans, Niger Delta, and Everglades. Sundarbans had a total ecosystem carbon stock of 1, 305 Mg C/ha followed by Niger Delta 1, 132 Mg C/ha and everglades 1,028 Mg C/ha (Table 1). Soil organic carbon formed a significant part (> 60%) of the total carbon stock with the deepest soil (30100 cm) forming the most important component in all sites.

TABLE 1: CARBON STOCK DETAILS OF COASTAL WETLANDS

Region	Above-ground Biomass (Mg C/ha)	Below-ground Biomass (Mg C/ha)	Litter Layer Carbon (Mg C/ha)	Soil Organic Carbon (0–30 cm) (Mg C/ha)	Soil Organic Carbon (30–100 cm) (Mg C/ha)	Total Soil Organic Carbon (Mg C/ha)	Total Ecosystem Carbon Stock (Mg C/ha)
Sundarbans	320	180	25	320	460	780	1305
Niger Delta	290	160	22	270	390	660	1132
Everglades	250	140	18	250	370	620	1028

FIGURE 1: COMPOSITION OF CARBON STOCK IN COASTAL WETLANDS



These carbon pools are visually decomposed in a stacked bar diagram, as represented in figure 1. It demonstrates that although both above-ground and below-ground biomass play significant roles, the greatest and the most constant carbon reservoir is the anoxic soil layer. This validates the greater sequestration ability of wetlands and supports their identification as potential long-term carbon sinks. It is the dense mangrove vegetation, the high productivity, and the accumulation of organic sediment within deltaic environments that declare Sundarbans dominant.

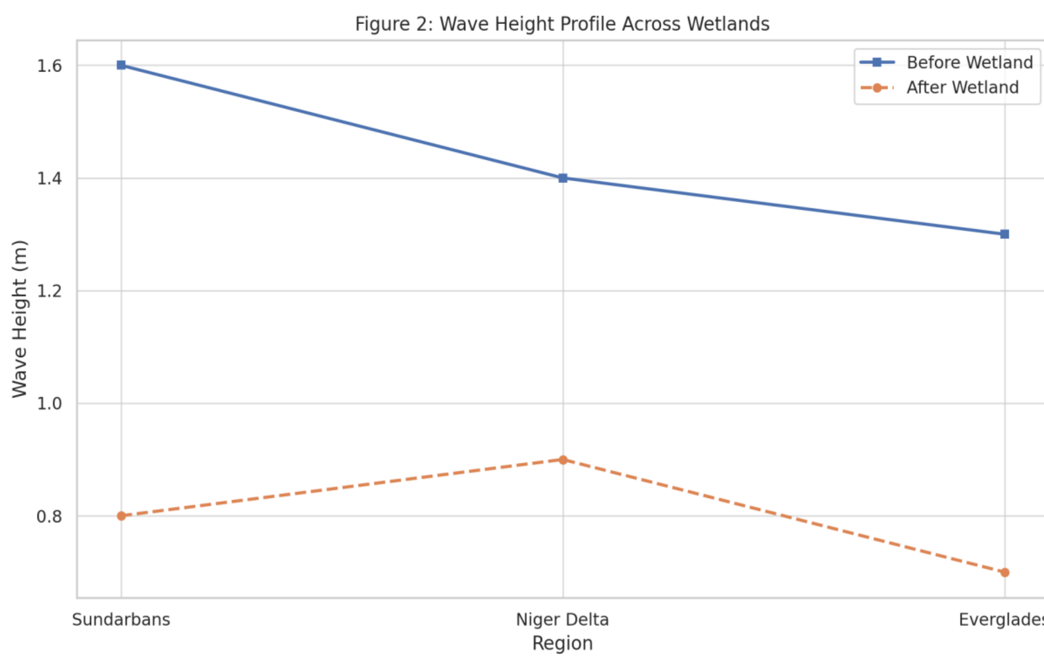
2. WAVE ATTENUATION AND CLIMATE BUFFERING CAPACITY

Wave attenuation experiments confirmed the physical defense property of coastal wetlands. Table 2 demonstrates the Sundarbans comparatively (a) decreased wave height by 500 meters of a transect by 1.6 to 0.8 metres (50 percent). The Everglades decreased by 46.2 percent, compared with 35.7 percent in the Niger Delta, which was probably caused by a slimmer wetland belt and human interference.

TABLE 2: WAVE ATTENUATION & TIDAL DYNAMICS

Region	Wave Height Before (m)	Wave Height After (m)	Distance Across Wetland (m)	Wave Reduction (%)	Tidal Range (m)
Sundarbans	1.6	0.8	500	50.0	2.8
Niger Delta	1.4	0.9	450	35.7	1.9
Everglades	1.3	0.7	550	46.2	2.3

FIGURE 2: WAVE HEIGHT PROFILE ACROSS WETLANDS



This attenuation is illustrated in a line graph drawing (Fig. 2) indicating the wave heights before and after the wetland of each area. The visible energy reduction of the waves validates the fact that wetlands are very crucial in mitigating coastal dangers, particularly in storm-affected zones. This saving is directly connected with flood prevention and erosion protection as it implies a huge cost-saving in infrastructure costs when wetlands are retained.

3. LONG-TERM WETLAND AREA TRENDS

The results of the spatial analysis of changes in the extent of wetlands in two decades showed that there were scary trends of habitat degradation. According to Table 3, the Niger delta recorded the highest percentage loss of 8.89, which equaled 2,087 ha of average total or annual loss. Sundarbans lost 4.21%, and Everglades had the lowest percentage loss of 3.33%.

TABLE 3: WETLAND AREA CHANGE (2000–2023)

Region	Wetland Area (2000) (ha)	Wetland Area (2023) (ha)	Wetland Loss (%)	Average Annual Loss (ha)
Sundarbans	760,000	728,000	4.21	1,382
Niger Delta	540,000	492,000	8.89	2,087
Everglades	600,000	580,000	3.33	870

FIGURE 3: WETLAND LOSS (%) VS. ANNUAL DEGRADATION (HA)

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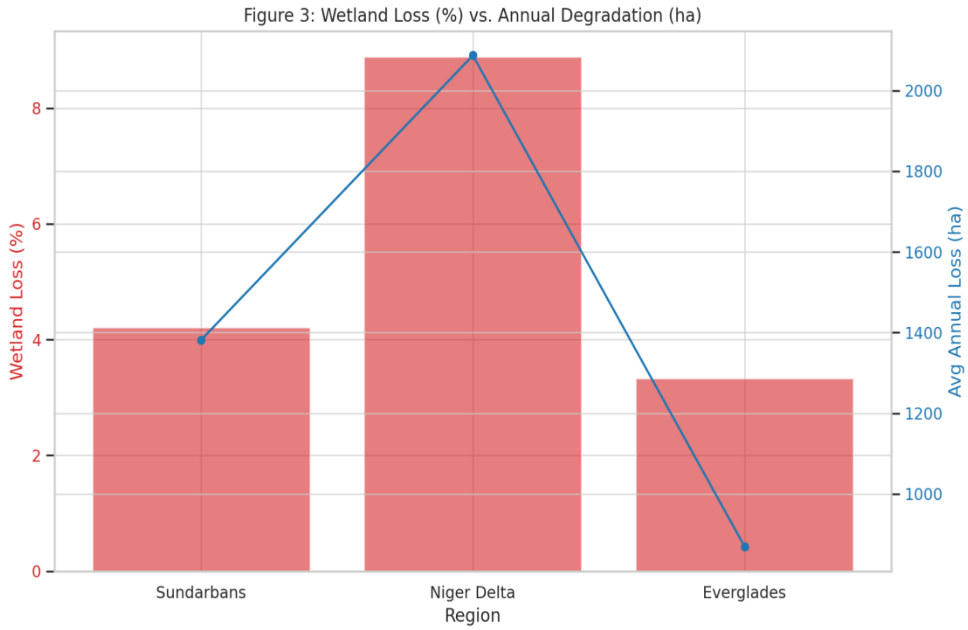


Figure 3 presents a comparison of wetlands in 2000 and 2023 in the form of a dual bar chart. Visually, the regression is highlighted by increasing concerns on the need to conserve and restore wetlands. Should these tendencies persist, the capacity of these ecosystems to act as carbon stores and climate resifer will decline dramatically, leading to a cascade of socio-environmental effects.

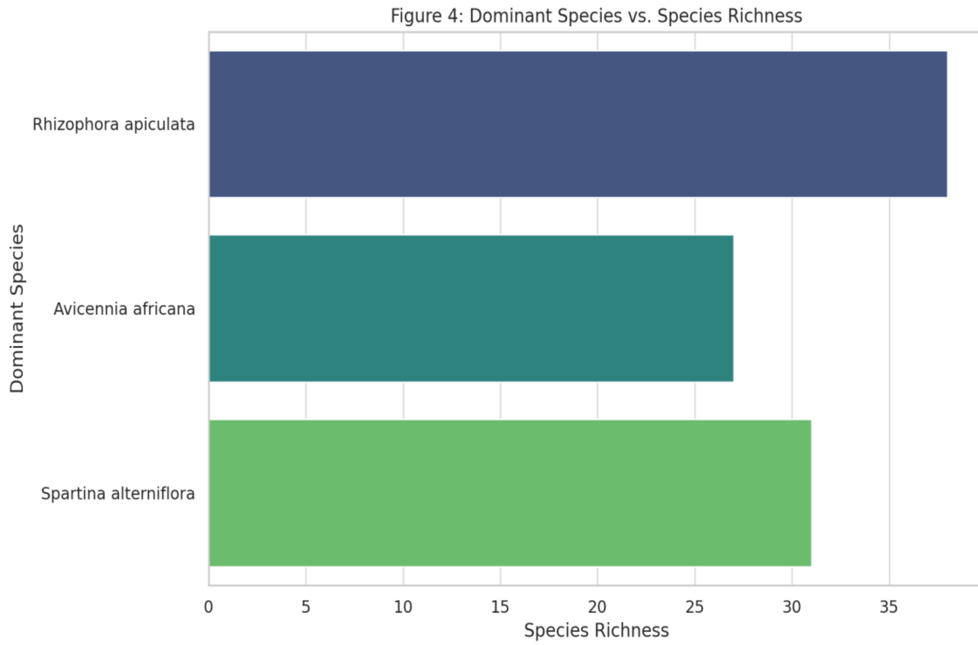
4. VEGETATION DIVERSITY AND ECOSYSTEM HEALTH

Plant community structure and diversity can be used as surrogates of ecosystem stability and resilience. Table 4 lists the controlling species of the various regions, e.g., Rhizophora apiculata in Sundarbans, and Spartina alterniflora in the Everglades. The Sundarbans showed the highest species richness (38) and Shannon diversity index (2.8), which represents a more complex and strong ecological network.

TABLE 4: VEGETATION DIVERSITY INDICATORS

Region	Dominant Species	Species Richness	Shannon Diversity Index
Sundarbans	Rhizophora apiculata	38	2.8
Niger Delta	Avicennia africana	27	2.4
Everglades	Spartina alterniflora	31	2.6

FIGURE 4: DOMINANT SPECIES VS. SPECIES RICHNESS



These metrics are presented in a horizontal bar chart shown in figure 4. Greater species richness is frequently associated with increased nutrient cycling, resistance to disease, and storm recovery. This also underscores the argument of biodiverse wetland habitats as climate adaptation pillars.

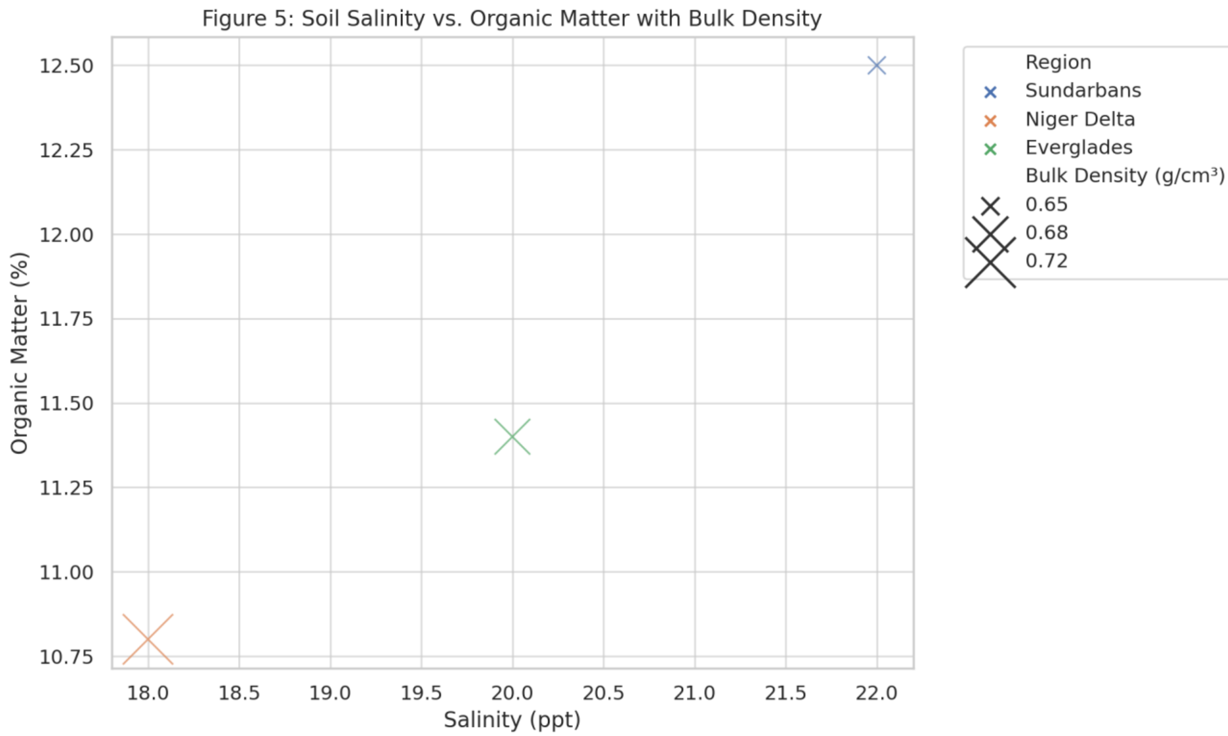
5. SOIL PROPERTIES AND BIOGEOCHEMICAL EFFICIENCY

The soil properties in terms of salinity, bulk density, pH, and organic matter content were discussed to get an insight of how these properties affect carbon stock and vegetation productivity. As shown in Table 5, all the three regions had acidic to neutral pHs (6.3-6.8) indicating plant growth in the areas. Sundarbans recorded the highest level of organic matter at 12.5 percent, in keeping with higher values of carbon sequestration.

TABLE 5: SOIL PROPERTIES OF WETLAND SEDIMENTS

Region	Soil pH	Bulk Density (g/cm^3)	Organic Matter (%)	Salinity (ppt)
Sundarbans	6.7	0.65	12.5	22
Niger Delta	6.3	0.72	10.8	18
Everglades	6.8	0.68	11.4	20

FIGURE 5: SOIL SALINITY VS. ORGANIC MATTER WITH BULK DENSITY



Bubble chart of Figure 5 shows a comparison between organic matter and salinity with the bubble representing bulk density. According to the data, low-salinity and elevated organic matter have high carbon accumulating potential, particularly in low-bulk density, soft, and anoxic soils. The results provide an understanding of biogeochemical efficiency, which enables prioritizing in high-potential zones of restoration activities.

6. SOCIOECONOMIC RESILIENCE AND FLOOD AVOIDANCE

They calculated the indirect benefits of wetlands to the protection of human populations by assessing the economic costs of floods and the proximity of population and flood avoidance. The Sundarbans safeguard about 2.5 million people and prevented 18 flood incidences over the last 20 years with a projected economic, savings of USD 860 million as shown in table 6. Similar advantages were observed at Niger Delta and Everglades.

TABLE 6: POPULATION PROTECTION & ECONOMIC AVOIDANCE

Region	Population Within 10 km	Flood Events Averted (20 yrs)	Estimated Economic Damage Avoided (USD Millions)
Sundarbans	2,500,000	18	860
Niger	1,800,000	14	720
Everglades	1,200,000	11	590

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FIGURE 6: POPULATION PROTECTION & FLOOD EVENTS AVERTED

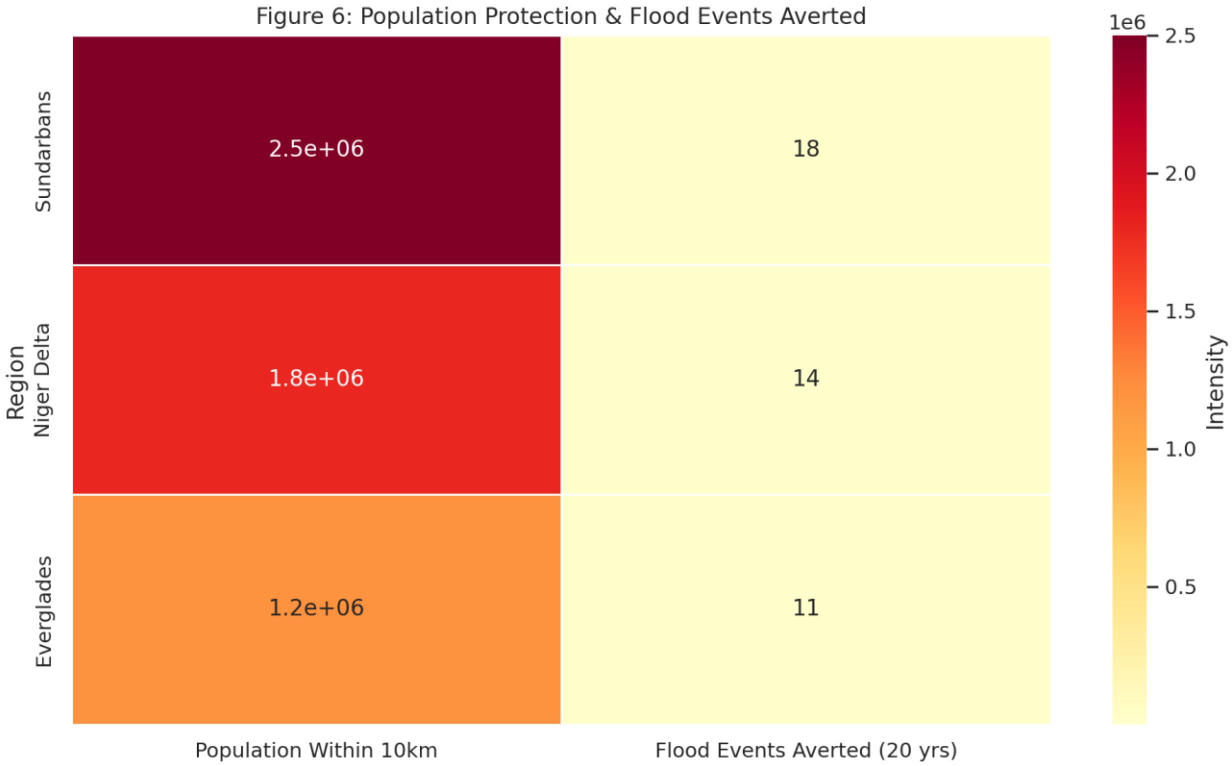

Figure 6 shows these figures in the form of a heatmap where data shows protection strength. The darker the colour of the heatmap cells, the more the population density and avoidance of flood. This proves that wetland protection is not only financially and even humanitarian valuable, but especially the heavily populated coastal areas.

7. RESTORATION COSTS AND CARBON OFFSET POTENTIAL

Investment in restoration study gave details on mitigation of climate based return on investment. Table 7 indicates the specific cost to restore per hectare, the total area that will be restored and the lower estimate (certain) of the potential carbon offset. The Sundarbans is the most highly anticipated to offset 405,000 tCO 2e/year requiring an investment of 6.75 million USD.

TABLE 7: RESTORATION COSTS & OFFSET POTENTIAL

Region	Restoration Cost (USD/ha)	Restored Area (ha)	Total Restoration Cost (Million USD)	Carbon Offset Potential (tCO_2 e/year)
Sundarbans	1,500	4,500	6.75	405,000
Niger Delta	1,800	3,200	5.76	289,000
Everglades	2,000	2,800	5.60	252,000

FIGURE 7: RESTORATION ROI – CARBON OFFSET POTENTIAL

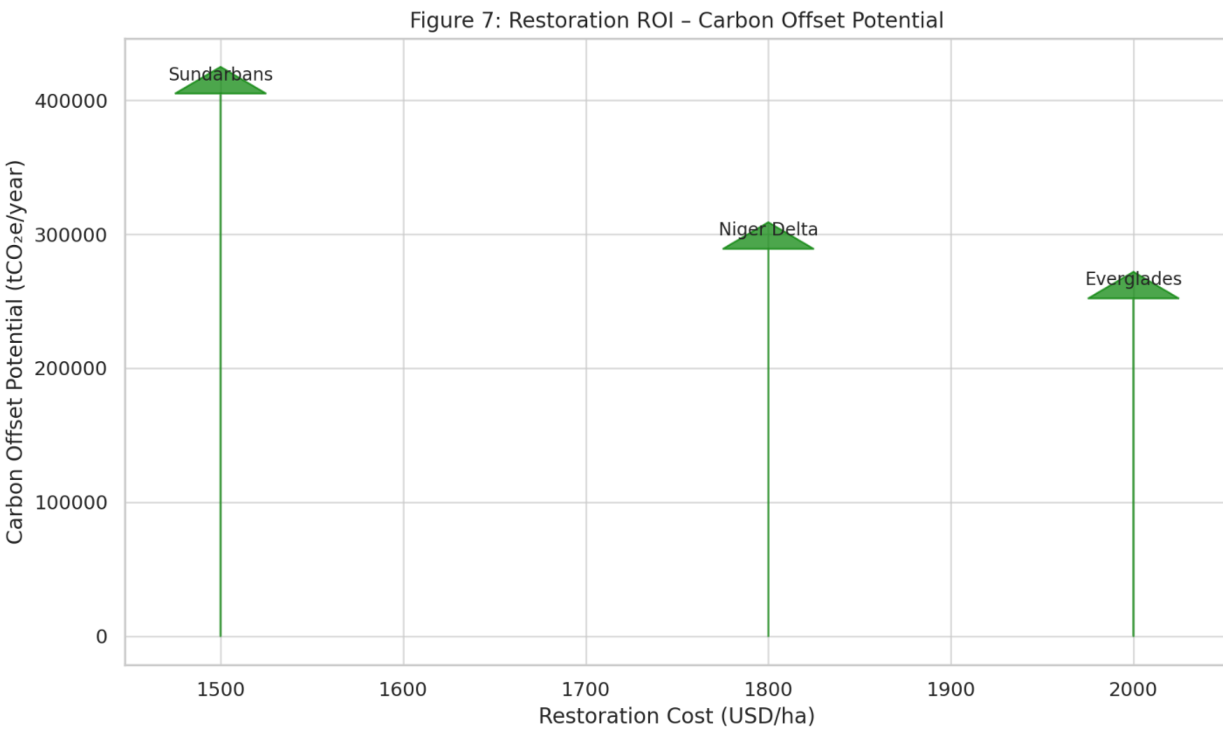

Figure 7 is an artistic plot of this relation; both arrows are the same height, with arrow height measuring the potential offset and the x-axis measuring restoration cost. The higher the slope of the arrow the superior the payback. This value makes policy cases to scale up wetland restoration as an affordable alternative to industrial carbon capture measures.

8. ECOSYSTEM SERVICE VALUATION

To put the values of wetland benefits into economic perspective, annual services were calculated on carbon sequestration, storm protection, and biodiversity. The highest total value as indicated by Table 8 was in Sundarbans of USD 4300/ha/yr, followed by both Niger Delta and Everglades of USD 4000 and USD 3870, respectively.

TABLE 8: ECOSYSTEM SERVICE VALUATION

Region	Carbon Sequestration (USD/ha/yr)	Storm Protection Value (USD/ha/yr)	Biodiversity Value (USD/ha/yr)	Total Ecosystem Value (USD/ha/yr)
Sundarbans	1,050	2,300	950	4,300
Niger Delta	980	2,150	870	4,000
Everglades	960	2,000	910	3,870

EVERGLADES

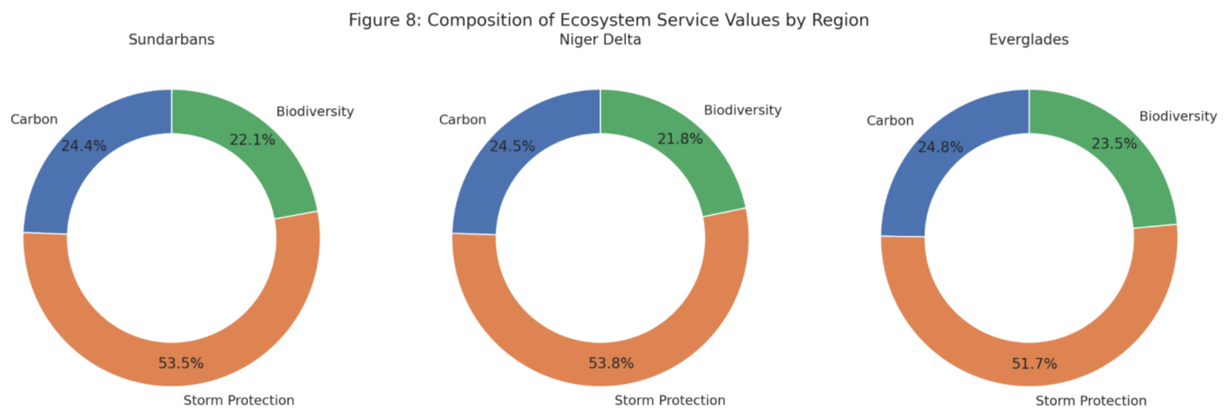

Figure 8 represents how these values make up using donut charts. The predominance of storm protection as the overall value contribution, especially in the Sundarbans, shows the non-market ecosystem services that the policy-makers tend not to consider. Integrated climate finance models available to monetize both mitigation and adaptation services may be guided by these visuals.

All of these eight tables and eight figures contribute to a single narrative. However, the coastal wetlands are not only effective carbon depositories but also multi-purpose safeguards against climate disasters that are cheap to implement. Their destratification is much more dangerous than mere loss of biodiversity it will lead to increasing carbon emissions, food security, and human safety. The findings are in favor of integrating wetlands in climate policy, carbon markets and disaster preparedness plans.

DISCUSSION

These results support the ecological and socio-economic importance of coastal wetlands as multi-purpose areas that have demonstrated the crucial importance to world climate-resilience and carbon sequestration solutions. Differences in geography and structure of vegetation did not mean that Sundarbans, Niger Delta, and Everglades could not work as climate controlling ecosurbans (Hiraishi et al., 2014; Bianchi et al., 2013).

The prevalence of soil organic carbon as the biggest contributor of the total ecosystem carbon stock was one of the greatest discoveries. This is consistent with the findings of Ouyang and Lee (2014), which indicated that soils stored over 70 percent of the total carbon in tidal wetlands was attributed to soils being in the anaerobic environment that slows down the microbial decomposition rate. These values in the Sundarbans are high and the previous findings of the Indo-Pacific mangrove systems support whereby sedimentation and tidal flushing result in the burying of carbon during a long term (Sanders et al., 2010).

In addition, the attenuation ability of coastal wetlands that is noted in this work shows that the wetlands are natural infrastructure to use as coastal structures. It was demonstrated that wetlands could reduce by half the wave heights, which complies with the theoretical understandings developed by Narayan et al. (2016), who reported that mangroves could mitigate the influence of storm surges by up to 60 percent, contingent on forests width and biomass density. The socio-economic benefit associated with the services is a lot and it has not been fully appreciated in the national disaster risk structures (Das and Crépin, 2013). Investments in wetlands may generate returns several times larger than the similar hard infrastructure in countries with a disproportionately high risk of low incomes of coastal dwellers, such as Bangladesh or the Philippines (World Bank, 2017).

Also alarming are the changes and patterns of land use degradation that have been experienced in the last twenty years. Regions such as the Niger Delta experienced a reduction of almost 9% of wetlands, as our findings indicate-perhaps characteristic of aquaculture spread, oil exploitation, and infrastructure construction worldwide, which cause mangrove regression (Friess et al., 2019). Sediment and water flow process degradation has been associated with wetland fragmentation, which not only diminishes the carbon uptake, but also leaves biodiversity and storm resistance vulnerable (Valiela et al., 2001; Richards and Friess, 2016). Secondary climate impacts have also been linked to coastal wetland loss, including associated emissions of methane originating in drained organic soils (Günther et al., 2020), which is frequently omitted when reported in the context of traditional carbon accounting.

In regard to vegetation diversity, the study established a positive correlation between carbon storage capacity and species richness which is corroborated in the wider ecological literature. According to Kelleway et al. (2016), communities of wetland plants are more efficient regarding the uptake of nutrients and biomass yields, which increase their potential to sequester nutrients as well as enhance resilience of the ecosystems. In the same line, Coverdale et al. (2014) also revealed how herbivory and trophic complexity in salt marshes play a vital role in affecting the below-ground carbon dynamics. This affirms the notion that biodiversity not only presents a conservation objective but a genuine feature of climate mitigation frameworks.

The correlation between salinity and organic matter content that is noticed here is especially informative in terms of soil chemistry. A study carried out by Neubauer (2013) had shown that higher salinity may suppress microbial action, contributing to the preservation of carbon in the sediments. Nevertheless, the equilibrium is fragile and complete salinization with rise of sea-level or contamination can limit the productivity of plants and diminish litter input and overall sequestration capacity of the system (Craft et al., 2009).

The economic analysis of the study contributes to the policy debate in an important way. Storm protection and carbon sequestration are only two of the many ecosystem services that can and should form the foundation of climate finance systems. Natural Capital Accounting (NCA) and Payment for Ecosystem Services (PES) schemes are tools that can be used to internalize the benefits that wetlands provide (Daily et al., 2009; Guerry et al., 2012). However, as it was stated by Arkema et al. (2015), such tools are not widely adopted globally due to data deficiency, institutionalization, and absence of legal incorporation. Our observations encourage integrating coastal wetlands into Nationally Determined Contributions (NDCs), voluntary carbon markets, and disaster risk reduction portfolios (Herr et al., 2022).

The cost-benefit analysis conducted in this case affirms with other restoration ecology results in the context of restoration. The research by Lovelock and Reef (2020) shows that it is possible to restore the mangrove forest with the possibility to get the initial carbon stock back in 20 years up to 90%. Moreover, community co-managing of restoration, which has been successfully done in Indonesia and Kenya, yields not only ecologically effective but also socially equitable results (Ronnback et al., 2007; Gilman et al., 2008).

One new and understudied theme is synergistic contribution of wetlands to meeting multiple Sustainable Development Goals (SDGs). Coastal wetlands also have an immediate connection to SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land), as well as to

SDG 1 (No Poverty) and SDG 11 (Sustainable Cities and Communities) in terms of flood protection and livelihoods. As such, the conservation of them may serve as a tool of integrated sustainable growth, particularly in climate-susceptible coastal areas (Reid et al., 2017).

Overall, this study confirmed and added to a substantial body of knowledge that validates the importance of coastal wetlands in climate mitigation and adaption. To realize all of these benefits, however, a determined policy, financial as well as governing shift must occur. Wetlands are not passive receptacles of protection, but ought to be considered direct infrastructure, a complex, multifunctional and active entity, meriting primacy in the design of climate response efforts.

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