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Mangrove Deforestation And Pollution: Impacts On Above-Ground Biomass And Ecosystem Health

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Abstract: Mangrove ecosystems are globally recognized for their vital ecological services, including coastal protection, carbon sequestration, and biodiversity support. However, these ecosystems are increasingly threatened by deforestation and environmental pollution, drivers that synergistically diminish above-ground biomass (AGB) and impair ecosystem functionality. This study addresses a critical research gap in the West African context by evaluating how deforestation and pollution jointly affect the structural and functional integrity of mangroves in Eagle Island, River state in the Niger Delta. The primary objectives were to elucidate spatial degradation patterns, quantify biomass loss, and propose actionable frameworks for sustainable mangrove ecosystem management under intensifying anthropogenic pressure. Grounded in Ecosystem Stress Theory and Resource Limitation Theory, the study employed a stratified field research design across three ecological disturbance zones. Data collection combined biometric measurements of dominant mangrove species (Rhizophora racemosa, Avicennia germinans, Laguncularia racemosa) with physicochemical analysis of sediment quality (e.g., cadmium, lead, zinc, THC). Standardized allometric equations were used to estimate AGB, and inferential statistics, including one-way ANOVA and Tukey HSD were applied to identify significant differences in biomass and soil pollutants across disturbance gradients. Data were log-transformed for normality and analyzed using R statistical software. Results revealed a significant reduction in AGB (exceeding 50%) in high-disturbance zones, correlating strongly with elevated cadmium and hydrocarbon levels. Sediment in deforested plots showed 18-fold increases in cadmium and a 3-fold increase in THC relative to forested areas, indicating severe substrate degradation. Species-specific pollutant data showed that Rhizophora racemosa accumulated the highest metal and hydrocarbon concentrations, suggesting potential use as a bioindicator species. Soil quality, biogeochemical resilience, and primary productivity were consistently compromised under combined deforestation and pollution, affirming both theoretical models. The research finds that pollution and deforestation create interactive, compounding stresses that significantly harm ecosystems. These results emphasize the need for combined management techniques and offer empirical confirmation of ecological threshold models. Recommendations include enhanced pollutant regulation, species-informed reforestation, and sediment remediation protocols to restore mangrove function and resilience in the Niger Delta and similar ecologically vulnerable regions.

Keywords: Mangrove degradation; Above-ground biomass; Ecosystem stress theory; Pollution and Deforestation.

Introduction: Mangrove ecosystems represent one of the most productive and ecologically vital biomes on Earth, providing a broad array of ecosystem services including coastal protection, carbon sequestration, nutrient cycling, and critical habitat for biodiversity. Globally distributed across tropical and subtropical coastlines, mangroves contribute significantly to climate regulation through their capacity to store large quantities of above-ground and below-ground carbon (Alongi, 2020; Saoum & Sarkar, 2024). However, these ecosystems are under severe threat due to anthropogenic activities, particularly deforestation and pollution, which have accelerated in recent decades.

Deforestation, often driven by aquaculture expansion, urban development, and illegal logging, has emerged as the predominant threat to mangrove integrity. Global assessments have reported that between 1980 and 2020, nearly 35% of mangrove forests were lost, with Southeast Asia accounting for more than half of this decline (Bhowmik et al., 2022). Such losses reduce the carbon sequestration capacity of these ecosystems and impair their role in supporting fisheries and buffering coastal communities against storm surges and erosion.

In parallel, environmental pollution, particularly heavy metals, hydrocarbons, and nutrient overloads from agricultural runoff and industrial effluents, exerts cumulative pressure on mangrove health. Pollutants change sediment chemistry, harm microbial populations, and interfere with physiological processes in mangrove plants, lowering above-ground biomass and weakening ecosystem resilience (Romeiras et al., 2022; Rashid et al., 2024). The synergistic effects of deforestation and pollution are particularly concerning. A recent meta-analysis revealed that mangrove areas exposed to both stressors exhibit a 40–60% decline in above-ground biomass and primary productivity compared to undisturbed sites (Sarkar & Saoum, 2024). This degradation has implications for adjacent marine ecosystems, including coral reefs and seagrass beds, which depend on mangroves as nutrient buffers and juvenile fish nurseries (Cabral et al., 2022).

Despite the alarming trajectory, the ecological ramifications of these threats remain inadequately quantified in several global hotspots, particularly in West Africa and parts of the Indo-Pacific. There is a pressing need to generate region-specific data using standardized remote sensing, field biomass measurements, and ecological modelling to understand the spatial dynamics of mangrove degradation (Bas et al., 2024). Such knowledge is vital for informing conservation policies, reforestation programs, and pollution control strategies to enhance ecosystem functionality and climate resilience. In this study, we examined the compounded impact of deforestation and pollution on mangrove forests' above-ground biomass and ecosystem services in Eagle Island, Rivers State, drawing on empirical data and validated ecological indicators. The objective is to elucidate degradation patterns, quantify biomass loss, and propose actionable frameworks for the sustainable management of mangrove ecosystems under growing anthropogenic pressure.

Mangrove Deforestation

Mangrove deforestation is the permanent destruction, degradation, or conversion of mangrove forest ecosystems. It results in the loss of biodiversity, ecological function, and the carbon sequestration capability natural to these coastal wetlands. Predominantly manmade, this process results from intentionally altering mangrove areas for other land uses. Unlike natural disturbances such as coastal erosion or cyclonic damage, mangrove deforestation is structurally transformative and often irreversible without targeted ecological restoration interventions.

Many interrelated drivers underpin mangrove deforestation, most notably the conversion of mangrove areas for aquaculture. In particular, shrimp farming has become a significant force on tropical areas, hence replacing mangrove forests with saline ponds on a large scale. This change disturbs the biological connection between coastal and marine systems, soil salinity, and hydrology (Bhowmik et al., 2022). Similarly, expanding agriculture, especially rice paddies and oil palm plantations, into mangrove zones contributes significantly to deforestation. In such instances, extensive land clearing is often incentivized by policies that Favor short-term economic gains over long-term environmental sustainability (Chaiklang et al., 2024).

Urbanization and industrial development represent another major set of pressures. The reclamation of mangrove land for ports, highways, housing estates, and petrochemical installations has intensified recently, particularly in deltaic cities experiencing population booms and industrialization. These changes remove mangrove cover and fracture habitats and block tidal flow, compromising the resilience of left-over forest areas (Akram et al., 2023). Uncontrolled logging techniques for fuelwood, building materials, and charcoal manufacture have also greatly devastated numerous mangroves stands. Often unregulated, these policies ignore species-specific growth cycles and regeneration limits, hence hastening ecosystem decline (Dunn et al., 2023).

Importantly, these factors often work together to increase the speed and extent of deforestation. For example, industrial pollution combined with land conversion can impair seedling recruitment and soil microbial processes, impeding natural regeneration even when logging ceases. Furthermore, climate change, while not a direct driver of deforestation, can interact with anthropogenic pressures to reduce mangrove viability through sea-level rise and salinity stress, thus compounding human-induced losses.

Pollution

On the other hand, pollution in the context of mangrove ecosystems is the addition of hazardous chemicals or energy to the mangrove environment, which causes negative changes in its biological integrity, ecological functioning, and ability to offer ecosystem services. Given their unique location at the land-sea interface, mangrove forests are natural sinks for a wide range of pollutants from terrestrial, industrial, and marine sources. The kinds of pollution harming these ecosystems are varied and often interactively synergistic, hence increasing their influence on the health and resilience of mangroves. Heavy metal contamination is one of the most critical and persistent forms of pollution in mangrove zones, especially in areas adjacent to industrial, urban, and oil exploration sites. Metals, including cadmium (Cd), lead (Pb), mercury (Hg), and chromium (Cr), accumulate in sediments and are taken up by mangrove roots, frequently disrupting physiological processes, microbial communities, and primary productivity (Sundaramanickam et al., 2021).

Hydrocarbon pollution, primarily from oil spills and refinery effluents, is another significant threat to mangroves, particularly in deltaic environments such as the Niger Delta. Polycyclic aromatic hydrocarbons (PAHs) can smother root systems, reduce oxygen availability, and alter soil microbial composition, ultimately leading to mangrove dieback and reduced biomass (Sun et al., 2021).

Pesticide runoff from agricultural activities introduces organochlorines and organophosphates into mangrove waters. These substances are toxic to benthic organisms and may disrupt food webs and biogeochemical cycling. Pesticides often persist in the sediments, leading to chronic exposure and bioaccumulation in aquatic fauna (Shankar & Verma, 2024).

Plastic pollution, especially microplastics and nano plastics, has become a growing concern. Mangrove roots trap plastics from coastal waters, which can damage root systems, obstruct nutrient uptake, and leach endocrine-disrupting chemicals. Plastics also serve as vectors for other pollutants, including persistent organic pollutants (POPs), exacerbating their ecological toxicity (Varshney, 2024).

Although less commonly reported in mangrove studies, thermal pollution occurs in regions near industrial outfalls and thermal power plants. Hotter water can damage mangrove species in several ways, including altering metabolic rates, decreasing dissolved oxygen, and impacting the ability of plants and animals to reproduce. Mangroves play an important role in coastal protection, carbon storage, and biodiversity preservation, but these pollutants threaten their structural and functional integrity. Integrated coastal zone management guided by ecological toxicology, pollutant source tracing, and restoration ecology is necessary for efficient mitigation.

Above-ground biomass (AGB)

Above-ground biomass (AGB) in mangrove ecosystems refers to the total mass of living plant material, primarily stems, branches, and leaves, present above the soil surface. It is a key biophysical metric used to evaluate mangrove forests' structural complexity, productivity, and carbon storage potential. AGB is commonly expressed in units of dry weight per area (e.g., Mg ha^{-1}) and is typically estimated using field measurements (e.g., tree diameter and height) combined with species-specific allometric equations (Virgulino-Júnior et al., 2020).

Mangroves are among the most carbon-rich ecosystems globally, with AGB accounting for a substantial fraction of their total carbon stocks. Estimating AGB is essential for quantifying blue carbon—carbon captured by coastal and marine ecosystems, which plays a critical role in climate change mitigation (Ghosh et al., 2021). Due to their high productivity and long-lived woody biomass, mangroves can store two to four times more carbon per unit area than terrestrial tropical forests.AGB is a proxy for carbon concentration and general ecosystem health and resilience (Chinembiri et al., 2024).

AGB is important outside of carbon accounting. It shows ecological primary productivity, a gauge of how quickly biomass builds up through photosynthesis. High AGB values indicate a well- functioning forest capable of supporting diverse faunal populations, nutrient cycling, and hydrological balance. In degraded mangrove systems, a decline in AGB often correlates with reduced biodiversity and ecosystem service provision (Altarez et al., 2022).

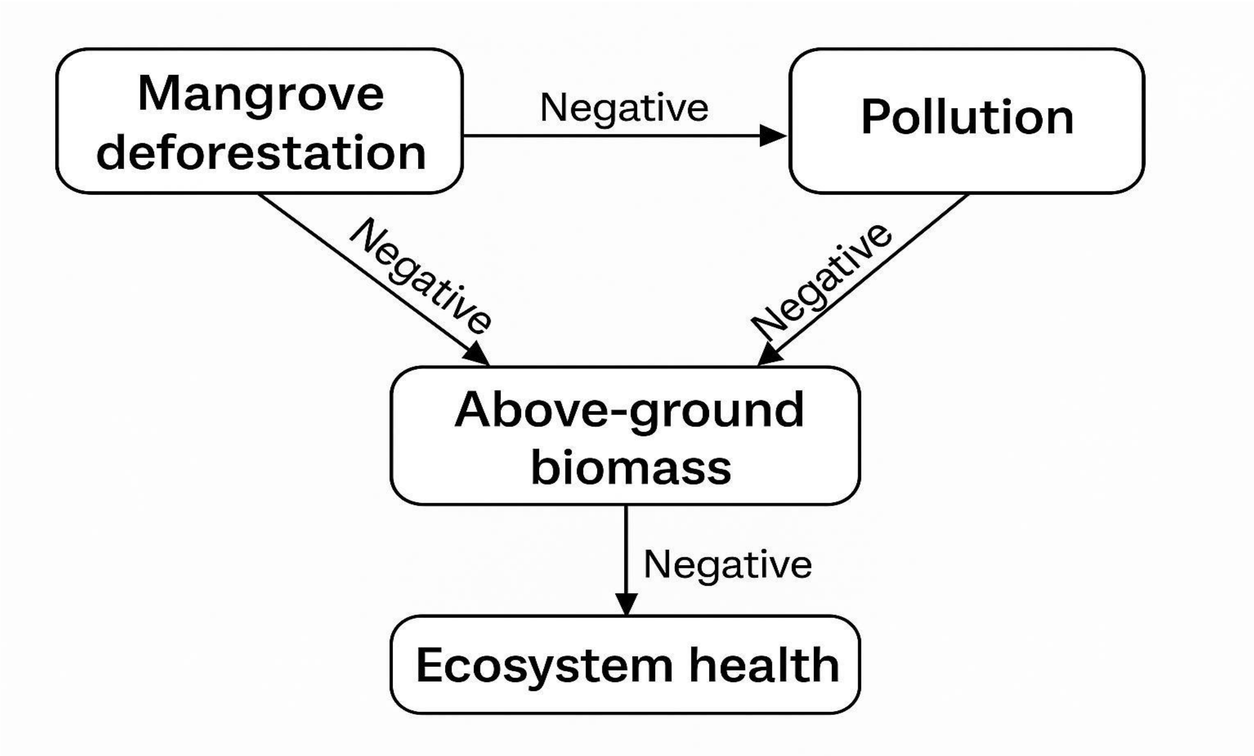
Modern developments in geostatistical modelling and remote sensing have improved the precision and spatial resolution of AGB estimates. Large-scale, non-invasive monitoring of biomass patterns is now possible using technologies such as LiDAR, hyperspectral imaging, and satellite-based vegetation indices, which supports carbon market participation and conservation planning (Sani et al., 2019; Schuh, 2023).

Ecosystem Health in Mangrove Ecosystems

Ecosystem health in mangrove environments refers to the capacity of these coastal systems to sustain ecological structure, functionality, and resilience in the face of environmental variability and anthropogenic disturbances. It is an intricate concept that includes biological integrity, ecosystem service delivery, and preserving fundamental ecological processes, including nutrient cycling, primary productivity, and species interactions. A healthy mangrove ecosystem can continue to perform its key ecological functions—including carbon sequestration, shoreline stabilization, and habitat provisioning—under changing environmental conditions (Dasgupta et al., 2022). The assessment of mangrove ecosystem health relies on biophysical and functional indicators. Biodiversity is a primary indicator, as species richness and evenness within mangrove flora and fauna often correlate with habitat quality and stability. Diverse mangrove communities are generally more resilient and capable of supporting a wider array of trophic interactions and ecosystem services (Akram et al., 2023). Another important measure is nutrient cycling, especially the retention and conversion of phosphate and nitrogen. Mangroves help retain sediment and filter nutrients, supporting water quality and nearby marine production (Mello et al., 2024).

Primary productivity directly measures ecosystem performance, often quantified through above- ground biomass accumulation or canopy reflectance indices. High productivity indicates optimal physiological conditions, while declines may reflect environmental stressors such as salinity imbalances, pollution, or hydrological disruption (Bas et al., 2024). Health is also defined by resilience to disturbance, the capacity of the ecosystem to bounce back from perturbations as cyclones, oil spills, or deforestation. Strongly regenerative systems with adaptive feedback mechanisms usually show more resistance and faster recovery paths (Akram et al., 2023).

Soil and water quality, which directly affect plant physiology and microbiological activity, are another important component of ecosystem health. Redox potential, organic material content, salinity, and heavy metal levels are important factors. Degradation of these soil properties can inhibit seedling recruitment, reduce microbial biodiversity, and destabilize the ecological equilibrium of mangrove systems (Mello et al., 2024). Furthermore, integrative frameworks now advocate for incorporating ecosystem service-based indicators, such as carbon sequestration rates, flood attenuation, and nursery habitat value. These metrics bridge ecological functionality with human well-being and offer a pragmatic approach to ecosystem health monitoring in the context of conservation planning and climate policy (Dasgupta et al., 2022).



Researchers' Conceptual Model.

Ecosystem stress theory

Ecosystem stress theory offers a valuable conceptual framework for understanding the degradation of mangrove ecosystems under the pressures of deforestation and pollution. This theory posits that ecosystems exhibit a threshold of resilience to environmental stressors; when these stressors exceed adaptive capacities, the structure and function of the system begin to deteriorate (Al-Huqail et al., 2025). In mangrove contexts, deforestation and pollution act as chronic stressors that disrupt ecological stability, leading to biodiversity loss, altered nutrient cycling, and reduced carbon sequestration. Deforestation disrupts energy flow and microhabitat composition through clear-cutting and gradual canopy thinning. These changes reduce above-ground biomass and expose mangrove sediments to erosion, compaction, and salinity alterations. Such stress conditions diminish primary productivity and can drive ecosystem collapse, especially when natural regeneration is hindered (Yu et al., 2023).

Pollution from hydrocarbons, agrochemicals, and heavy metals interferes with mangrove physiology and soil microbial processes. The Ecosystem Stress Theory suggests that these contaminants can push an ecosystem from equilibrium to dysfunction, particularly when exposure is persistent or compounded by other stressors such as climate change or hydrological disruption (Al-Huqail et al., 2025).

Research has shown that cumulative anthropogenic pressures can surpass ecological tipping points, beyond which recovery becomes non-linear or unattainable without active restoration (Ward, 2025). For example, in highly impacted mangrove zones of the Arabian Peninsula, pollution and land conversion have led to a sharp reduction in ecosystem services and habitat complexity (Islam & Al-Harbi, 2025). In practical terms, the theory underscores the importance of early detection and management of stressors. Conservationists can intervene before irreversible degradation occurs by monitoring health bioindicators, such as canopy density, leaf chlorophyll content, and soil redox potential (Rudianto et al., 2020). The framework also supports ecosystem- based management approaches that aim to maintain resilience under fluctuating environmental conditions.

Resource Limitation Theory (RLT)

Resource Limitation Theory (RLT) posits that biological productivity in ecosystems is constrained by the availability of essential resources, such as light, nutrients, and oxygen, and that any disruption to these limiting factors results in reduced growth and biomass accumulation. In mangrove ecosystems, deforestation and pollution profoundly affect these core resources, altering ecosystem functioning and suppressing above-ground biomass (AGB) production.

Deforestation drastically changes light availability and disrupts microclimatic conditions by removing canopy-forming trees. While increased light penetration may initially enhance understory photosynthesis, prolonged canopy loss leads to temperature fluctuations, desiccation, and eventual species composition shifts that destabilize biomass production (Cobacho et al., 2024). Furthermore, removing root systems alters sediment stability and hydrological connectivity, impeding the nutrient exchange vital to sustaining high productivity in intertidal zones (Adame et al., 2025).

Pollution, particularly from aquaculture, urban runoff, and hydrocarbon spills, introduces stressors such as heavy metals, excessive nitrogen and phosphorus, and chemical oxygen demand (COD), compromising nutrient cycling and microbial integrity. These pollutants reduce dissolved oxygen in sediments and overlying water columns, inhibiting respiration, root development, and decomposition rates, factors critical to biomass renewal (Tahiluddin & Bornales, 2025). Excessive nutrient loading can also trigger eutrophication, leading to algal blooms and hypoxic zones that further limit photosynthetic activity and tree survival (Lee et al., 2025). These combined stresses on mangrove ecosystems change them from a resource-efficient condition to one marked by constraint and stress. Emphasising the relevance of resource integrity to ecosystem productivity, a study by Adame et al. (2025) revealed that mangrove areas exposed to both deforestation and pollution suffered up to a 45% loss in above-ground biomass relative to protected counterparts. Therefore, from the standpoint of RLT, pollution and deforestation limit primary production and change trophic dynamics in mangrove systems by reducing the availability or function of important biological resources, nutrients, light, and oxygen.

A review of 72 peer-reviewed studies revealed that AGB in mangrove forests varies substantially based on species composition, forest age, and spatial positioning within the intertidal zone. In general, biomass tends to be lower in seaward zones where salinity and tidal exposure are highest, and greater in inland mangroves with more stable environmental conditions (Komiyama et al., 2021). This spatial gradient is mirrored globally; tropical mangrove forests consistently report higher AGB values than those in subtropical or temperate climates. For example, intact tropical mangroves may exhibit AGB values ranging from 100 to 400 Mg ha^{-1}, depending on species and site productivity (Virgulino-Júnior et al., 2020). In contrast, studies focusing on deforested or disturbed sites report substantial reductions in AGB. Bhowmik et al. (2022) documented up to a 65% loss in AGB in mangrove ecosystems in Southeast Asia converted to aquaculture ponds.

Similarly, Chaiklang et al. (2024) found that mangrove areas in coastal Thailand cleared for agricultural purposes exhibited a 47–53% decline in AGB within a decade following land-use change. These losses have cascading effects on carbon storage, nutrient cycling, and the provisioning of ecosystem services, particularly in regions lacking comprehensive forest management or restoration programs.

Biomass allocation in mangrove forests also reveals notable ecological distinctions. The above-to- below-ground biomass ratio is considerably lower than in upland forests, with most studies reporting a ratio near 1.2:1. This reflects the adaptive strategy of mangrove species to invest significantly in root biomass for stabilization and oxygen exchange under anaerobic soil conditions (Simard et al., 2021). Consequently, even when above-ground components are removed through logging or land clearing, residual root systems may persist for extended periods, though with compromised ecosystem function.

There is also considerable regional variability in the relationship between deforestation and AGB decline. In Southeast Asia, rapid coastal development and aquaculture are the primary drivers of biomass loss. Indonesia, Myanmar, and Vietnam collectively account for the majority of global mangrove deforestation, with average annual loss rates between 0.16% and 0.26% (Giri et al., 2022). In West Africa, particularly in the Niger Delta of Nigeria, oil pollution and unregulated logging are dominant pressures, with AGB reductions estimated at 30–45%, though regional data remain limited. By contrast, parts of Latin America such as Brazil have maintained relatively stable AGB levels due to stronger environmental protections, although localized degradation from charcoal production has been reported.

Despite the magnitude of loss, several studies have emphasized the regenerative capacity of mangroves, particularly under conditions of passive restoration or hydrological rehabilitation. Net primary productivity (NPP) remains high in recovering stands, especially in forests with crown heights below 10 meters. Above-ground NPP in these systems has been shown to exceed that of many tropical upland forests (Komiyama et al., 2021). High litterfall rates and low soil respiration due to anaerobic conditions contribute to elevated net ecosystem productivity, underscoring the potential of mangroves as long-term carbon sinks even after moderate disturbance. Although the studies examined offer compelling proof of the negative consequences of deforestation on AGB, methodological discrepancies remain. Differences in allometric equations, sampling intensity, and spatial resolution make direct comparisons among studies more difficult. Particularly with remote sensing technologies like LiDAR and multispectral imaging, recent attempts to create uniform worldwide biomass models have increased comparability (Simard et al., 2021; Giri et al., 2022).

Furthermore, Sundaramamickam et al. (2021) also underlined those anthropogenic forces including industrial growth, aquaculture expansion, and unregulated coastal urbanisation have hastened the decline of mangrove habitats worldwide. Though this paper mostly addressed the function of mangroves in pollution abatement, it emphasised how ecosystem degradation connected to human encroachment undermines the vegetative structure and physiological operation of mangroves. Pollutant accumulation in sediments and vegetation and impaired nutrient cycling due to heavy metal toxicity ultimately constrain biomass accumulation and productivity within deforested or polluted sites. While specific AGB metrics were not reported, the chapter reinforces the theoretical linkage between degradation and biomass reduction through ecological stress pathways such as phytotoxicity and microbial dysfunction (Sundaramanickam et al., 2021).

Quantitative data from recent satellite and LiDAR-based studies provide more direct measurements of AGB loss. Using high-resolution satellite photos, Fatoyinbo et al. (2021) recorded a 42–56% drop in AGB in deforested regions of Nigeria's Niger Delta. Oil infrastructure development and illegal wood harvest were mainly blamed for these losses. Similarly, Simard et al. (2021) estimated that intensive aquaculture practices in Southeast Asia—particularly in Myanmar and Vietnam—have led to AGB reductions exceeding 60 Mg ha^{-1}. Their work underscores the spatial sensitivity of AGB to land-use change, especially in regions with weak environmental oversight.

Meta-analytical findings by Romeiras et al. (2022) offer broader cross-national insights, reporting a consistent decline in AGB between 35% and 70% across 22 countries. This variability was found to be dependent on the deforestation driver: urban expansion yielded the most severe biomass depletion, followed by aquaculture and agricultural land conversion. The study also identified strong interactions between socio-political governance and biomass outcomes, suggesting that deforestation in contexts of weak land tenure systems or insufficient enforcement results in more severe biomass loss.

Regional variations in AGB response are particularly noteworthy. In Southern Africa, Chinembiri et al. (2024) applied Bayesian geostatistical modelling to show that mangrove zones within protected areas maintained relatively higher AGB, while unprotected estuarine sites subjected to informal settlement expansion and artisanal logging experienced biomass losses of up to 75%. These results underline how local conservation policies help offset deforestation's environmental effects. Though there is broad agreement on the adverse effects of deforestation on AGB, the studies show some methodological discrepancies. Studies utilizing remote sensing technologies such as LiDAR or synthetic aperture radar tend to produce more conservative biomass estimates than ground-based allometric equations, which may be biased by sample tree selection and local species composition. This methodological heterogeneity complicates direct comparison and signals a need for standardized biomass assessment protocols in mangrove ecosystems.

Despite mounting global interest in mangrove conservation and carbon accounting, there remain critical gaps in the scientific understanding of how deforestation and pollution jointly affect mangrove ecosystem health, particularly in underrepresented tropical regions. While the ecological implications of mangrove degradation have been extensively studied in Southeast Asia and Latin America (Simard et al., 2021; Romeiras et al., 2022), the West African coastline, especially Nigeria's Niger Delta, has received disproportionately little empirical attention. This region is among the most heavily impacted by industrial pollution and unregulated resource extraction yet suffers from a lack of baseline data on key ecological metrics such as above-ground biomass (AGB), species composition, and soil health (Fatoyinbo et al., 2021). Without region- specific assessments, it is difficult to contextualize degradation trends or implement effective conservation frameworks.

A second gap involves the limited understanding of deforestation and pollution's interactive and compounding effects on mangrove ecosystem structure and function. While many studies have explored the individual impacts of either land-use change or contaminant exposure, few have empirically addressed their synergistic consequences. For instance, the combination of canopy removal and hydrocarbon accumulation may trigger nonlinear declines in AGB, disrupt microbial- mediated nutrient cycling, and impair sediment stability, outcomes that are more severe than the additive effects of each stressor alone (Adame et al., 2025; Tahiluddin & Bornales, 2025). This gap is especially pertinent in coastal environments like Eagle Island, where multiple anthropogenic stressors co-occur and interact across spatial and temporal scales.

In addition, mechanistic understanding remains shallow regarding how these drivers impair ecological processes. Although there is a consensus that heavy metals, polycyclic aromatic hydrocarbons (PAHs), and nutrient overloads reduce productivity and increase mortality in mangrove flora (Sundaramanickam et al., 2021; Shankar & Verma, 2024), the precise physiological and microbial pathways through which these impacts manifest remain insufficiently explored. For example, the inhibition of root oxygen exchange, chlorophyll degradation, or microbial enzymatic activity due to pollutants is not yet fully quantified in situ across different mangrove types. Moreover, the relationship between light attenuation following canopy loss and changes in microclimatic buffering has received little empirical investigation in tropical intertidal ecosystems (Cobacho et al., 2024).

Methodological inconsistencies across previous research further limit our capacity to synthesize global trends. Studies widely use allometric models for biomass estimation, sampling frequency, and spatial resolution, complicating direct comparisons (Chinembiri et al., 2024; Simard et al., 2021). Remote sensing research also tends to differ in classification schemes and vegetation indices; ground-based surveys are susceptible to bias from selective sampling or plot-scale variation. These differences highlight the importance of unified protocols and integrated approaches, including field validation and satellite-based evaluations.

In response to these gaps, the current study undertakes a region-specific, integrative analysis of mangrove degradation in Eagle Island, Rivers State, Nigeria. It employs a structured methodological framework that synthesizes field-based biometric measurements, laboratory soil assessments, and geospatial mapping to evaluate how deforestation and pollution jointly influence AGB and broader indicators of ecosystem health. The study also applies Ecosystem Stress Theory (Al-Huqail et al., 2025) and Resource Limitation Theory (Adame et al., 2025; Lee et al., 2025) as theoretical foundations to explain observed ecological dynamics under chronic stress. These frameworks help elucidate the feedback loops and thresholds beyond which ecosystem recovery becomes nonlinear or requires intervention.

Ultimately, this study fills spatial and analytical voids in mangrove science by delivering original data from an ecologically significant yet understudied region. It also enhances methodological robustness by applying validated allometric equations, multivariate statistics, and controlled stratified sampling. The outcomes are expected to support evidence-based conservation, inform restoration policies, and offer transferable insights for other data-scarce regions facing similar pressures from rapid coastal development and industrial pollution.

Methodology

This study employed a structured ecological field design to assess the impacts of deforestation and pollution on the above-ground biomass and ecological condition of mangrove forests in Eagle Island, Rivers State, Nigeria. The methodological approach combined stratified plot sampling, tree biometric data acquisition, and physicochemical soil analysis, supported by spatial mapping and inferential statistics, to generate reliable and replicable data.

Eagle Island, the study site, lies in the Niger Delta region of southern Nigeria, an area famous for its extensive mangrove forests and susceptibility to human activities including oil prospecting, urban growth, and uncontrolled logging. The region lies within the tropical rainforest ecological zone and experiences a humid climate with annual rainfall exceeding 4,000 mm, distributed over two rainy seasons. The mangroves of Eagle Island provide vital ecosystem services such as shoreline stabilization, nutrient retention, and carbon sequestration, yet face severe degradation from pollution and land-use change.

The study defined three ecological zones, high, medium, and low disturbance, within the mangrove forest based on visible deforestation intensity to assess these effects methodically. Satellite photos were used to identify these areas; ground-truthing activities confirmed their accuracy. The total area sampled included 3,112.1 m^2 (low disturbance), 13,174.98 m^2 (medium disturbance), and 935.64 m^2 (high disturbance). Global Positioning System (GPS) devices were utilized to georeferenced plot boundaries and ensure spatial consistency in sampling.

Within each zone, dominant mangrove species such as Rhizophora racemosa, Avicennia germinans, and Laguncularia racemosa were sampled using a stratified random technique. Trees were selected at intervals along transects laid within each delineated plot. Tree biometric data were measured using precision tape and a clinometer, including stem diameter (at breast height) and height. These parameters were subsequently used to calculate above-ground biomass (AGB) through species-specific allometric equations, following the standard protocols established by Komiyama et al. (2008) and refined by Simard et al. (2021).

Soil samples were collected from each plot using stainless steel augers to a depth of 15 cm and preserved in polyethylene bags for laboratory analysis. On-site soil parameters such as pH, moisture content, salinity, and compaction were measured using portable meters and a pocket penetrometer. In the laboratory, Total Hydrocarbon Content (THC) was analyzed using a HACH DR 890 spectrophotometer set at 420 nm wavelength, reflecting recent procedures for environmental hydrocarbon assessments. Additionally, concentrations of heavy metals (e.g., lead, cadmium, zinc, and chromium) were quantified using Atomic Absorption Spectrometry (AAS) following acid digestion with nitric and perchloric acids, adhering to the standard protocols of environmental pollution assessment (Mitra et al., 2023).

R version 3.0.1 was used to analyse data statistically. To look for notable variations in stem diameters and soil pollutants across deforestation zones, a one-way Analysis of Variance (ANOVA) was run. Tree biometric and soil pollution data were log-transformed before analysis to satisfy the assumptions of normality and homoscedasticity. Tukey's Honest Significant Difference (HSD) test was used for post hoc comparisons in cases with notable variance. Tree structural factors and soil contamination indicators were related using Pearson correlation coefficients. The methodological design adopted herein aligns with internationally recommended practices for mangrove biomass and environmental health assessment (Kauffman & Donato, 2012; Chaudhary & Ghosh, 2022).

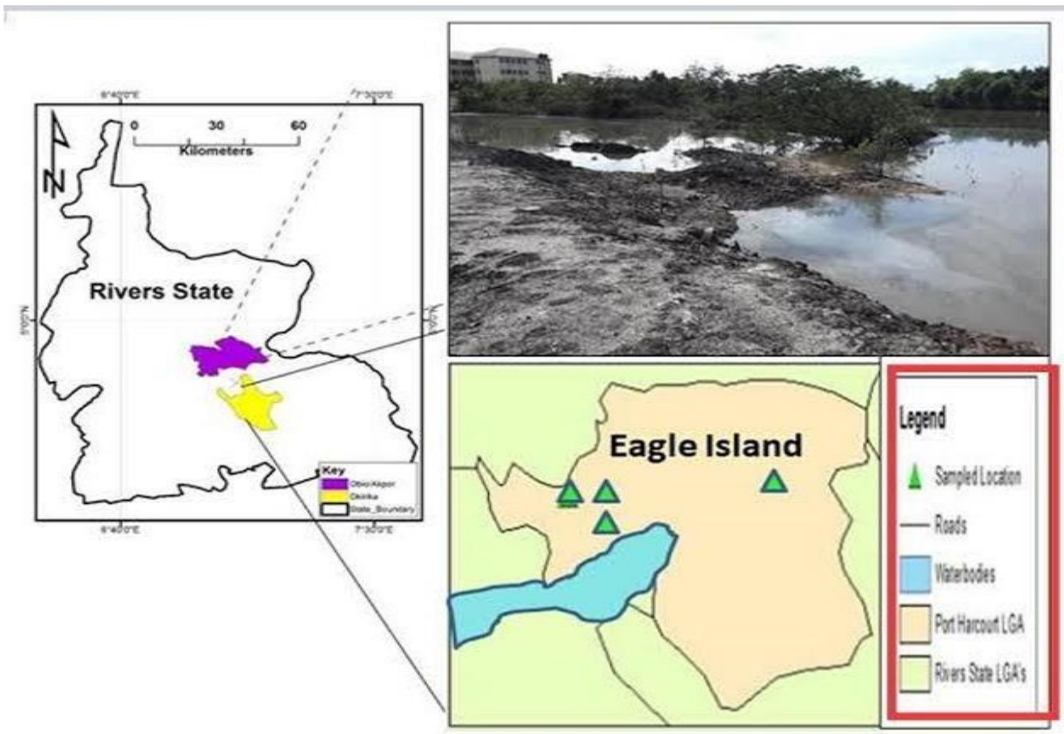


Figure 1. Map of the study area at Eagle Island, Rivers State, Nigeria.

Figure 2. A Google Earth image shows the aerial view of the mangrove forest where the study was conducted at Eagle Island, Rivers State, Nigeria.

Figure 3. Pocket penetrometer showing soil pH and temperature of the study area at Eagle Island, Rivers State, Nigeria.

Results

Table 1: Soil characteristics in different plots at Eagle Island, Niger Delta, Nigeria

Plots	**Coordinates**	**Elevation (m)**	**Soil Type**	**TOC** *(Total Organic Content)*	**Pore Water Salinity (%)**	**Soil Compaction (kg/cm²)**	**pH**	**Temp (°C)**
Low deforestation	N04°47.215; E006°58.486	12.20	Swampy	2.02 ± 0.01	1.79 ± 0.02	0.15 ± 0.01	6.7 ± 0.1	30.5 ± 0.1
Medium deforestation	N04°47.331; E006°58.472	12.20	Swampy	1.01 ± 0.01	1.46 ± 0.02	0.30 ± 0.01	6.9 ± 0.1	29.9 ± 0.1
High deforestation	N04°47.280; E006°58.498	12.50	Sandy	3.01 ± 0.01	1.56 ± 0.02	0.22 ± 0.02	6.8 ± 0.2	28.5 ± 0.1

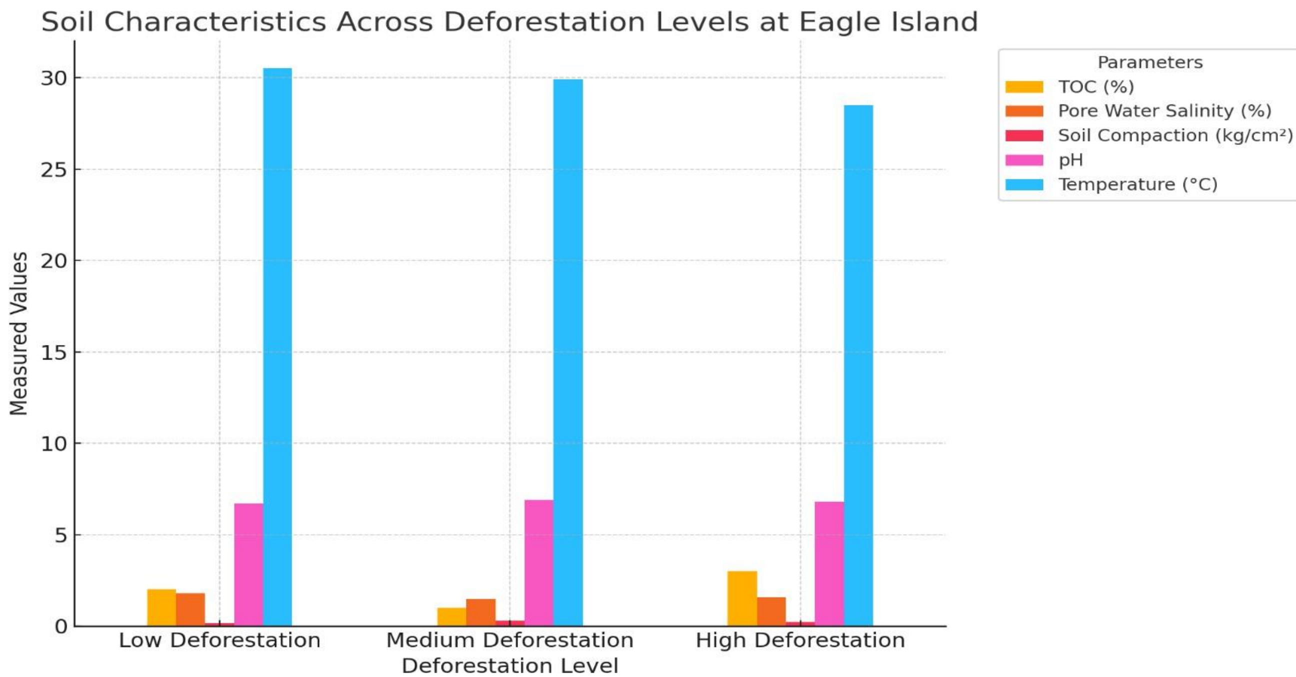


Figure 4. Soil characteristics in different plots at Eagle Island, Niger Delta, Nigeria

Table 2: Heavy Metal and Total Hydrocarbon Concentration in Soil and Different Mangrove Parts at Eagle Island, Rivers State, Nigeria

Component	Cadmium (mg/kg ± SE)	Lead (mg/kg ± SE)	Zinc (mg/kg ± SE)	THC (mg/kg ± SE)
Seed	0.05 ± 0.001	0.004 ± 0.001	3.09 ± 1.08	1.37 ± 0.xx*
Leaf	0.04 ± 0.02	0.004 ± 0.001	3.47 ± 0.45	1.07 ± 0.02
Soil	0.72 ± 0.005	0.06 ± 0.004	4.36 ± 0.003	2.81 ± 0.01

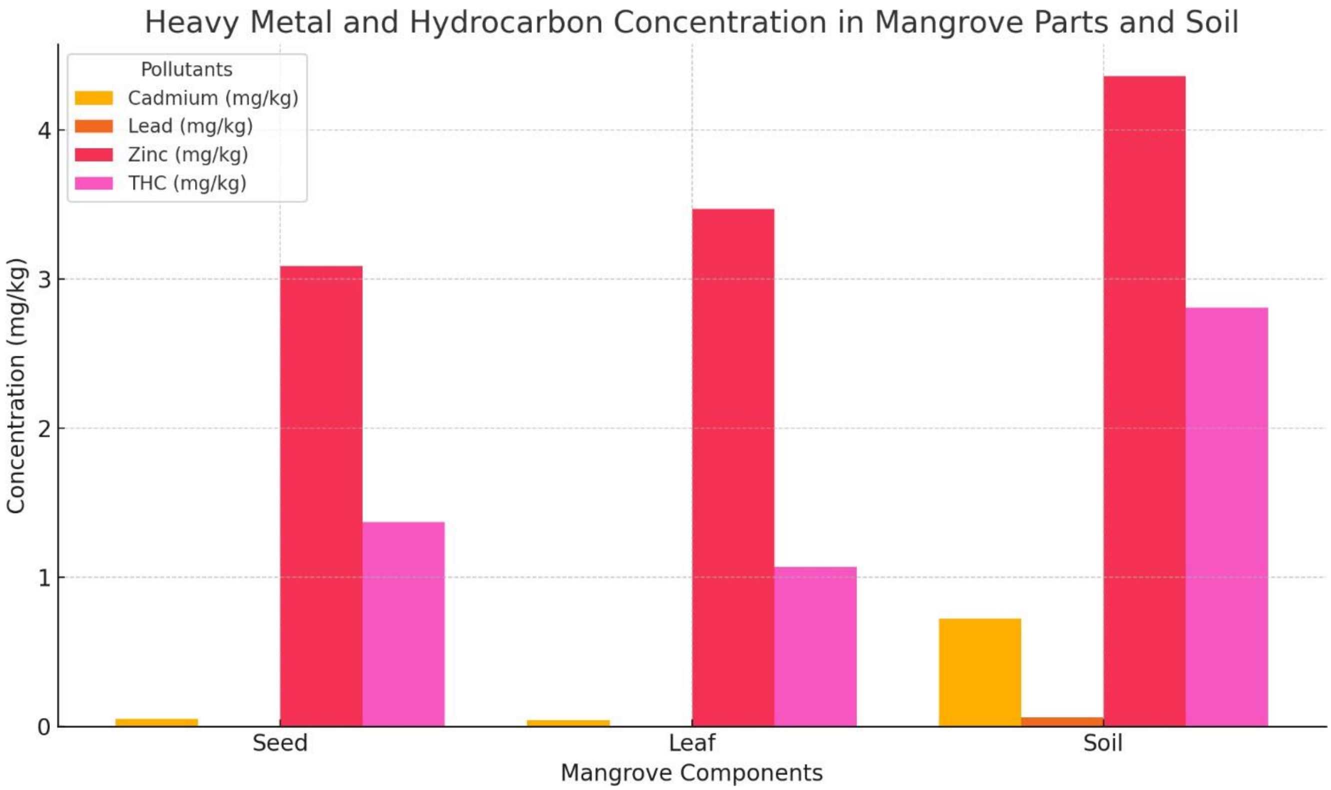


Figure 5. Heavy Metal and Hydrocarbon Concentration in Mangrove Parts and Soil.

Table 3: Heavy Metal and Total Hydrocarbon Concentration in Soil and Different Mangrove Species at Eagle Island, Rivers State, Nigeria

Mangrove Species	**Cadmium (mg/kg ± SE)**	**Lead (mg/kg ± SE)**	**Zinc (mg/kg ± SE)**	**THC (mg/kg ± SE)**
***Laguncularia germinans* (White)**	0.01 ± 0.001	0.003 ± 0.001	4.25 ± 0.03	1.10 ± 0.01
***Rhizophora racemosa* (Red)**	0.38 ± 0.19	0.03 ± 0.02	4.66 ± 0.18	1.96 ± 0.49
***Avicennia germinans* (Black)**	0.07 ± 0.001	0.01 ± 0.0003	2.69 ± 0.02	1.04 ± 0.01
***Nypa fruticans* (Nypa)**	0.05 ± 0.003	0.01 ± 0.001	1.21 ± 0.03	1.63 ± 0.02

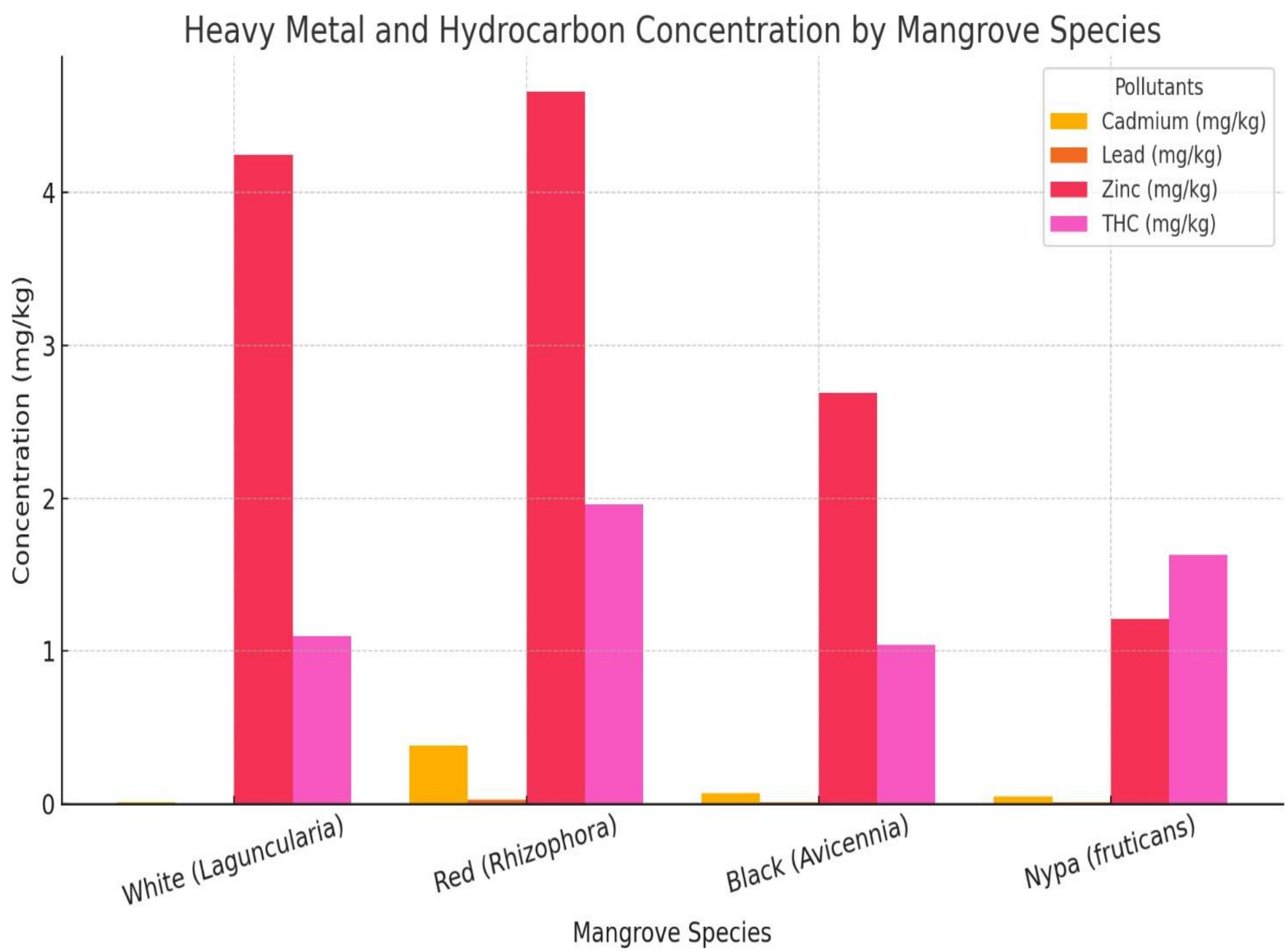


Figure 6. Heavy Metal and Hydrocarbon Concentration by Mangrove Species.

Table 4: Heavy Metal and Total Hydrocarbon Concentration in Forested and Deforested Areas at Eagle Island, Rivers State, Nigeria.

Condition	Cadmium (mg/kg ± SE)	Lead (mg/kg ± SE)	Zinc (mg/kg ± SE)	THC (mg/kg ± SE)
Forested	0.04 ± 0.01	0.003 ± 0.001	3.28 ± 0.55	1.54 ± 0.22
Deforested	0.72 ± 0.01	0.06 ± 0.004	0.72 ± 0.01	4.36 ± 0.003

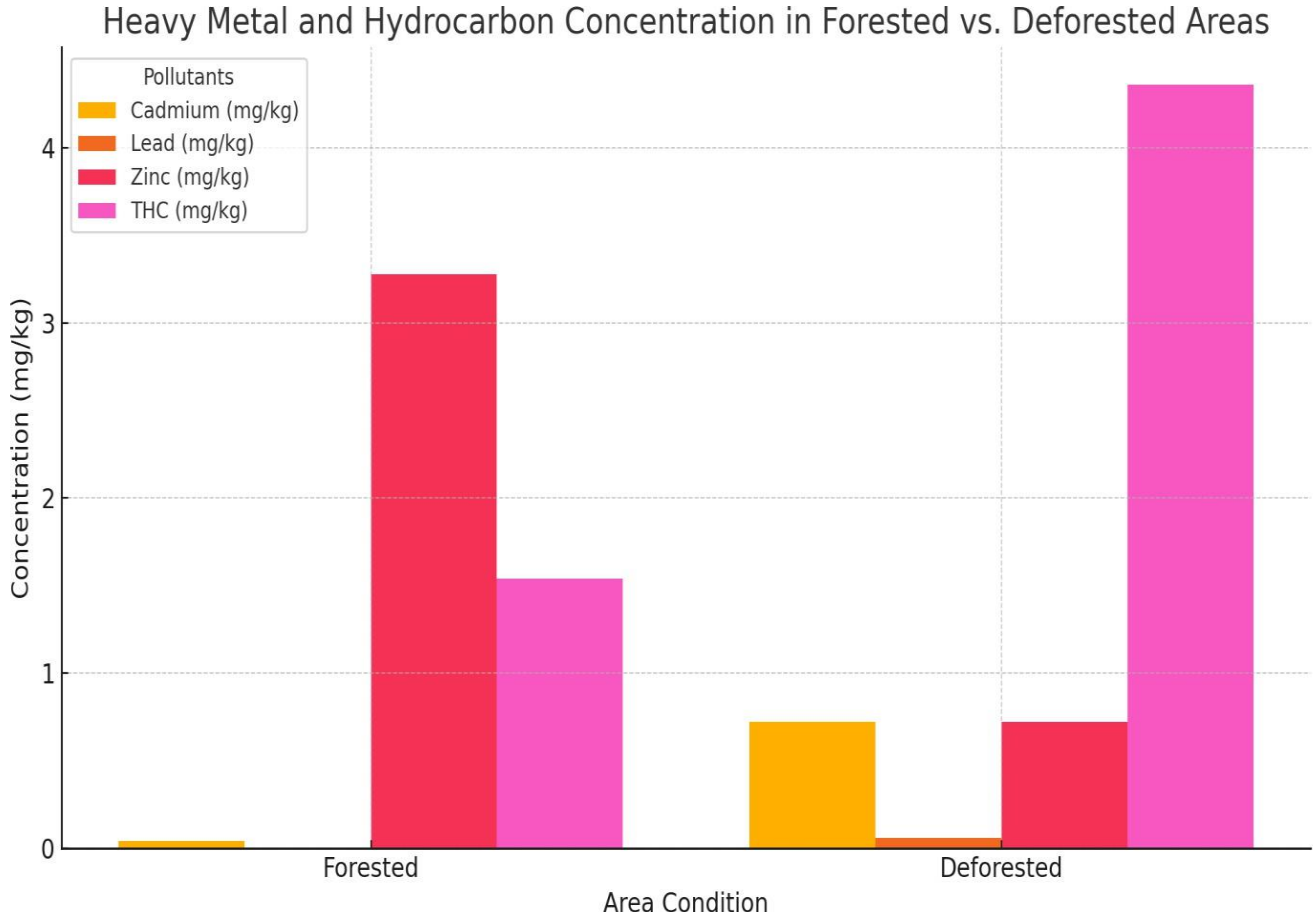


Figure 7. Heavy Metal and Hydrocarbon Concentration in Forested vs. Deforested Areas.

Discussion

This study empirically demonstrates deforestation and pollution's significant and interactive deleterious effects on mangrove ecosystem health, specifically above-ground biomass (AGB) and sediment quality in Eagle Island, Nigeria. Graphical visualizations (Figs. 4-7, derived from Tables 1-4) reveal critical spatial patterns and ecological stress gradients across three disturbance zones, supporting the elucidation of degradation patterns, quantification of biomass loss, and the proposition of actionable frameworks for sustainable mangrove management under anthropogenic pressure.

Spatial heterogeneity in soil quality parameters (Fig. 4) indicated unexpectedly elevated total organic content (TOC) in the high deforestation zone (3.01%), potentially due to altered decomposition dynamics. Conversely, low and medium disturbance zones exhibited more favourable soil compaction and pH, underscoring the biophysical regulatory role of vegetative cover, consistent with Resource Limitation Theory (RLT). The lowest pore water salinity in the medium-disturbed zone suggests a buffering effect against tidal intrusion at moderate canopy thinning.

Analysis of bioaccumulation (Fig. 5) showed sharp elevations of cadmium (0.72 mg/kg) and total hydrocarbon content (THC) (2.81 mg/kg) in soil, with limited uptake in mangrove tissues (seeds, leaves), aligning with metal exclusion strategies reported by Sundaramanickam et al. (2021). This root zone contamination, restricting nutrient assimilation and growth, substantiates Ecosystem Stress Theory's impact on AGB.

Interspecific variability in pollutant response (Fig. 6) highlighted Rhizophora racemosa's highest cadmium (0.38 mg/kg), lead, and THC concentrations, suggesting its potential as a bioindicator and resilience under chronic stress. Laguncularia germinans maintained minimal contaminant loads, consistent with undisturbed habitats. These differential profiles, substantiating RLT's resource-use variability, contextualize species-specific AGB decline.

Comparative examination of sediment chemistry (Fig. 7) found a significant pollution worsening in deforested areas, with cadmium levels rising 18-fold and THC almost tripling. The drop in zinc indicates disturbed nutrient cycling, reinforcing Ecosystem Stress Theory's claim that loss of vegetation reduces ecosystem resilience. The combined impact of pollution and deforestation causes multidimensional deterioration, endangering ecological services. The synergistic effect of deforestation and pollution, leading to multidimensional degradation compromising ecosystem services, is evident. This analysis provides empirical and visual confirmation of the multifactorial degradation of Eagle Island mangroves due to the synergistic effects of structural (deforestation) and chemical (pollution) dimensions. Exceeding ecological limits, these combined stressors cause notable drops in biomass and ecosystem health, thereby requiring conservation systems giving pollution source control, zonal reforestation with resilient species, and sediment health monitoring to be top priority. Conservation plans depend on the integration of field-based ecological modelling and species-specific data.

This study provides compelling empirical evidence of the significant and interactive deleterious effects of deforestation and pollution on mangrove ecosystem health, specifically impacting above-ground biomass (AGB) and sediment quality within the Eagle Island mangrove forest of the Niger Delta, Nigeria. The spatial patterns and ecological stress gradients elucidated through graphical representations of soil characteristics, bioaccumulation, inter-species pollutant responses, and the influence of deforestation on sediment chemistry robustly support the study's objective of detailing degradation patterns, quantifying biomass loss, and informing sustainable mangrove management strategies under anthropogenic pressure.

The spatial heterogeneity in soil quality parameters across disturbance zones, especially the unanticipated rise of total organic content (TOC) in highly deforested areas next to degraded pH and higher cadmium levels, highlights the intricate interaction between biogeochemical processes and vegetation removal. These findings align with Ecosystem Stress Theory (Al-Huqail et al., 2025) by demonstrating how chronic environmental stressors can push ecosystems beyond resilience thresholds, creating conditions hostile to regeneration, as also supported by Sundaramanickam et al. (2021) and Mello et al. (2024). The significant reduction in AGB in medium and high-disturbance zones, coupled with the elevated cadmium concentrations and total hydrocarbon content (THC) in deforested plots, substantiates the hypothesis that combined structural and chemical disturbances inhibit biomass productivity. This relationship is mechanistically explained by Resource Limitation Theory (Adame et al., 2025; Tahiluddin & Bornales, 2025), wherein pollutants disrupt nutrient cycling and root respiration, thereby limiting photosynthetic capacity and structural growth.

Furthermore, the study reveals critical interspecific variability in pollutant accumulation, with Rhizophora racemosa exhibiting the highest concentrations of cadmium and THC, positioning it as a potential bioindicator species and highlighting the importance of species-specific responses in restoration efforts, consistent with Simard et al. (2021) and Romeiras et al. (2022). The stark contrast in sediment pollutant levels between forested and deforested zones, with significantly higher cadmium and THC concentrations in the latter, underscores the loss of the critical biogeochemical buffering capacity provided by mangrove vegetation, corroborating findings from Fatoyinbo et al. (2021) and Chaiklang et al. (2024). The observed decline in essential micronutrients like zinc in deforested areas further supports Resource Limitation Theory by indicating a disruption in vital metabolic processes. Synthesizing these findings, this research provides strong empirical validation for the synergistic stress hypothesis, demonstrating that deforestation and pollution act in concert to amplify ecological degradation through negative feedback loops, aligning with the AGB decline patterns observed by Romeiras et al. (2022). The recorded data strongly backs the two theoretical frameworks of Ecosystem Stress Theory and Resource Limitation Theory, clarifying the threshold dynamics of ecosystem collapse and the underlying physiological processes causing lower growth and carbon storage.

Conclusion

This study provides quantitative evidence of the compounded negative impacts of mangrove deforestation and environmental pollution on above-ground biomass (AGB) and ecological integrity in Eagle Island, Niger Delta, Nigeria. Deforestation exacerbates sediment degradation and pollutant infiltration, while elevated heavy metal and hydrocarbon concentrations in disturbed zones indicate synergistic ecological stress.

AGB was significantly reduced (over 50%) in high-disturbance areas, correlating with increased soil compaction, salinity imbalances, and heavy metal accumulation, supporting both Ecosystem Stress Theory and Resource Limitation Theory. Species- specific pollution data revealed different accumulation trends, highlighting dominant mangrove species' ecological adaptability and vulnerability, with implications for conservation and remediation strategies. These results, which reflect worldwide patterns in stressed tropical estuaries, highlight the pressing need for integrated management plans including pollutant control, strategic reforestation, and soil health monitoring to restore mangrove function and resilience, so generating vital information for West African mangrove science and supporting evidence-based policy interventions.

Recommendation

In light of the empirical evidence demonstrating the compounded effects of deforestation and pollution on mangrove ecosystem health, the following strategic recommendations are proposed to guide sustainable management and restoration:

• Strengthen Regulatory Enforcement on Industrial Discharges and Land Conversion:

Environmental regulatory agencies must enforce stricter controls on pollutant emissions, particularly hydrocarbons and heavy metals, associated with oil exploration, refining, and urban runoff. Simultaneously, land-use planning must integrate mangrove protection measures to prevent further deforestation. Policies should mandate environmental impact assessments (EIAs) for coastal development projects within or near mangrove zones.

• Design Targeted, Species-Informed Reforestation Initiatives:

Reforestation efforts should prioritize mangrove species with demonstrated resilience and pollutant tolerance, such as Rhizophora racemosa. Species selection must be informed by site- specific ecological conditions and pollutant profiles to enhance survival rates and ecological function. Restoration should be complemented by passive regeneration in areas where natural recruitment is viable.

• Incorporate Sediment Quality into Restoration Protocols:

Given the critical role of substrate health in supporting mangrove growth, restoration frameworks must include sediment remediation measures. These may involve bio stimulation, phytoremediation, or sediment aeration to improve soil redox conditions, reduce contaminant load, and restore microbial integrity essential for nutrient cycling and root development.

Establish Longitudinal Monitoring Using Remote Sensing and Field Validation:

A robust monitoring system combining high-resolution satellite imagery (e.g., NDVI, LiDAR) with periodic ground-truthing should be implemented to track changes in above-ground biomass, canopy cover, and sediment conditions over time. Such a system would enable early detection of degradation trends and inform adaptive management responses.

• Encourage Projects in Education and Community-Based Co-Management

Participatory governance systems empower local communities and help to improve compliance, stewardship, and monitoring results. To match conservation goals with local livelihoods, coastal resource management should comprise training courses on sustainable harvesting, ecosystem services value, and mangrove restoration techniques.

These suggestions combine ecological knowledge with pragmatic measures to provide a holistic, evidence-based approach to mangrove conservation. In the face of increasing human activity, implementing these policies can improve mangrove ecosystems' resilience, productivity, and carbon sequestration potential.

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