

Spatial Assessment of Environmental Risks and Community Perceptions of Carbon Geosequestration for Blue Ecosystem Sustainability in the Niger Delta Nigeria

Udoh Evans

udohevans@gmail.com

University of Uyo

John Adeyanju

Maritime Academy of Nigeria

Bassey Ntukoghe

Maritime Academy of Nigeria

Research Article

Keywords: Subsurface formation, Greenhouse gas, Climate change, Sequestration, Blue-ecosystem

Posted Date: September 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10413429/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Geosequestration (carbon capture and storage, CCS), is increasingly recognized as a critical strategy for mitigating climate change. In Nigeria, its potential deployment within the Niger Delta raises important environmental and governance concerns because of the region's ecologically sensitive blue ecosystems. This study evaluated the spatial and socio-ecological implications of CCS for blue ecosystem sustainability using a mixed-methods approach that integrated GIS-based spatial analysis with community perception surveys. A total of 420 valid questionnaire responses were analysed using descriptive statistics and Pearson's Chi-square test. Spatial datasets were obtained from multiple authoritative sources, harmonized to the World Geodetic System 1984 (WGS 84) and Universal Transverse Mercator (UTM) Zone 32N coordinate system, and analysed within a GIS environment. The results revealed significant spatial overlap between regionally screened prospective CCS planning zones and ecologically sensitive blue ecosystems, including approximately 29.9% of mangrove forests and more than 23% of estuarine and marine habitats. Survey findings further revealed extremely low public awareness of CCS (over 95%) alongside high levels of perceived environmental risk. Statistical analysis demonstrated a significant association between public awareness and environmental risk perception ($\chi^2 = 24.6$, $p < 0.001$). These findings highlight a potential conflict between climate change mitigation objectives and biodiversity conservation, compounded by the absence of marine-specific regulatory provisions and limited stakeholder engagement. The study underscores the risk of undermining ecosystem resilience and coastal livelihoods if CCS is implemented without adequate environmental safeguards. It concludes that the sustainable deployment of geosequestration in Nigeria requires an integrated ecosystem-based and participatory governance framework supported by robust spatial planning, environmental regulation, and public awareness programmes.

INTRODUCTION

Climate change remains one of the most significant environmental challenges of the twenty-first century, with particularly severe consequences for developing countries because of their high ecological and socio-economic vulnerability (IPCC, 2022). In coastal regions such as the Niger Delta, rising temperatures, sea-level rise, coastal erosion, saline intrusion, biodiversity loss, and declining fisheries productivity increasingly threaten ecosystem integrity and the sustainability of the blue economy (Gattuso et al., 2018; Sun et al., 2023). Nigeria's blue ecosystem, comprising mangrove forests, estuaries, coastal wetlands, seagrass habitats, groundwater systems, and continental shelf waters, provides critical ecosystem services, including shoreline protection, fisheries production, biodiversity conservation, carbon sequestration, and livelihood support for millions of coastal inhabitants (UNEP, 2011; Jayeola & Olusola, 2022; Evans et al., 2014). However, these ecosystems continue to experience increasing pressure from oil pollution, habitat degradation, overfishing, and climate-induced environmental change (UNEP, 2011; Ghafouri, 2023).

Carbon Capture and Storage (CCS), commonly referred to as geosequestration, has emerged as one of the leading technological approaches for mitigating greenhouse gas emissions by capturing carbon

dioxide (CO₂) from industrial sources and injecting it into deep geological formations for long-term storage (Benson & Cole, 2008; IPCC, 2022). The Niger Delta Basin possesses favourable geological characteristics for CCS because of its thick sedimentary succession, depleted hydrocarbon reservoirs, deep saline aquifers, structural traps, and competent shale cap rocks within the Akata, Agbada, and Benin Formations (Jayeola & Olusola, 2022; Ajidahun et al., 2025). These geological conditions provide considerable opportunities for long-term carbon storage while supporting Nigeria's commitment to greenhouse gas emission reduction under the Paris Agreement (IEA, 2021).

Despite its climate mitigation potential, the deployment of CCS within environmentally sensitive coastal environments presents important ecological and governance challenges. Potential environmental risks include CO₂ leakage, groundwater contamination, seawater acidification, induced seismicity, and disturbances to benthic habitats, fisheries, mangrove ecosystems, and coastal livelihoods (Blackford et al., 2009; House et al., 2009; Katsanevakis et al., 2020; IPCC, 2022). These concerns are particularly important in the Niger Delta, where prospective geological storage formations coincide with biodiversity-rich ecosystems that already experience cumulative environmental pressures from petroleum exploration, oil spills, and climate change (Evans et al., 2014; O'Farrell et al., 2025). Furthermore, although Nigeria has enacted the Petroleum Industry Act (2021) and the Climate Change Act (2021), comprehensive regulatory provisions governing offshore carbon storage, long-term environmental monitoring, environmental liability, and stakeholder participation remain limited (IEA, 2021; Anna & Gasiokwu, 2024).

Globally, sustainable CCS implementation increasingly integrates geological suitability assessment with ecosystem-based management, marine spatial planning, environmental impact assessment, biodiversity conservation, and stakeholder engagement (Roberts et al., 2017; O'Leary et al., 2018; Gattuso et al., 2018; Li et al., 2022). While previous studies have independently investigated geological suitability for carbon storage or the ecological vulnerability of coastal ecosystems in Nigeria, relatively few have integrated geospatial suitability analysis, ecological sensitivity mapping, and community perceptions into a unified framework for environmentally sustainable CCS planning (Eigbe et al., 2024; Ogbo et al., 2024). Consequently, evidence remains limited regarding the spatial interactions between prospective geological carbon storage sites and ecologically sensitive blue ecosystems within the Niger Delta.

This study addresses this knowledge gap by integrating Geographic Information System (GIS)-based spatial analysis with community perception surveys to evaluate the environmental implications of geosequestration for blue ecosystem sustainability in the Niger Delta, Nigeria. Specifically, the study assesses stakeholder awareness of CCS, examines perceived environmental risks, analyses the spatial overlap between prospective carbon storage zones and ecologically sensitive environments, and proposes policy measures that support environmentally sustainable, socially inclusive, and scientifically informed deployment of geological carbon sequestration in Nigeria.

METHODOLOGY

Research Design

This study adopted a convergent mixed-methods research design integrating Geographic Information System (GIS)-based spatial analysis with a socio-environmental perception survey to evaluate the environmental implications of geological carbon sequestration (Carbon Capture and Storage, CCS) for the sustainability of the Niger Delta's blue ecosystems. The convergent design enabled the simultaneous collection and analysis of spatial and social datasets, after which the findings were integrated to provide a comprehensive assessment of potential interactions between prospective geological carbon storage suitability zones and environmentally sensitive coastal ecosystems.

The GIS component focused on identifying areas exhibiting favourable geological characteristics for potential carbon storage and evaluating their spatial relationships with ecologically sensitive environments, whereas the questionnaire survey examined stakeholders' awareness, perceptions, and concerns regarding CCS deployment. The integration of these complementary approaches provided a holistic understanding of both environmental vulnerability and community acceptance.

Study Area

The study was conducted within the coastal Niger Delta region of southern Nigeria, with particular emphasis on Akwa Ibom and Rivers States (Fig. 1). These states were purposively selected because they contain extensive hydrocarbon-producing fields, thick sedimentary formations suitable for geological carbon storage, ecologically sensitive coastal environments, and numerous communities whose livelihoods depend directly on fisheries and other blue economy resources.

The Niger Delta occupies approximately 70,000 km² along the Gulf of Guinea between latitudes approximately 4°00'–6°00'N and longitudes 5°00'–8°00'E. It is one of the world's largest deltaic systems and comprises extensive mangrove forests, freshwater swamp forests, tidal creeks, estuaries, wetlands, and shallow marine environments.

Geologically, the basin consists primarily of the Benin, Agbada, and Akata Formations, which contain depleted hydrocarbon reservoirs, deep saline aquifers, structural traps, and competent shale cap rocks that have been identified as favourable conditions for long-term geological storage of carbon dioxide. Despite these favourable geological characteristics, the region has experienced decades of environmental degradation arising from petroleum exploration, oil spills, gas flaring, shoreline erosion, wetland destruction, and coastal pollution, making it highly vulnerable to additional environmental disturbances.

Data Sources

The study utilised both spatial and socio-economic datasets. Spatial datasets were acquired from internationally recognised repositories and relevant national agencies to support the GIS analyses

(Table 1), while socio-economic information was obtained through field-based questionnaire surveys.

Table 1
Spatial Dataset and their Resolutions

S/N	Dataset	Spatial Resolution	Source	Purpose
1	Sentinel – 2 MSI	10m	Copernicus Open Access Hub	Land-cover classification
2	Landsat-8 OLI	30m	USGS Earth Explorer	Vegetation and land-use mapping
3	SRTM DEM	30m	USGS	Terrain and Hydrological analysis
4	Geological Map	1:250,000	Nigerian Geological Survey Agency	Geological suitability assessment
5	Depleted hydrocarbon fields	Vector	Nigerian Upstream Petroleum Regulatory Commission and published literature	Potential geological storage screening
6	Hydrological network	Vector	HydroSHEDS	Drainage and estuarine mapping
7	Mangrove distribution	Vector	UNEP-WEMC	Ecosystem sensitivity analysis
8	Marine Protected Areas	Vector	World Database on Protected Areas	Biodiversity assessment
9	GPS	3m	Field Survey	Ground verification

All spatial datasets were transformed into the World Geodetic System 1984 (WGS 84), Universal Transverse Mercator (UTM) Zone 32N coordinate reference system to ensure spatial consistency. Raster datasets were resampled to a common spatial resolution of 30 m prior to overlay analysis.

Geological Screening Criteria for Carbon Storage Site Selection

Regional geological screening was undertaken to establish whether the Niger Delta Basin possesses the minimum reservoir and seal characteristics required for secure geological carbon storage. Rather than performing detailed reservoir characterization at individual fields, this study adopted published screening criteria that have been widely applied in Carbon Capture and Storage (CCS) assessments within the Niger Delta Basin and other sedimentary basins.

The screening parameters include reservoir depth, porosity, permeability, reservoir thickness, cap-rock thickness, and structural integrity (fault density and sealing capacity). These parameters are

internationally recognised as the primary geological controls governing CO₂ injectivity, storage capacity, containment efficiency, and long-term storage security. Reservoirs located at depths greater than approximately 800 m permit injected CO₂ to remain in a dense supercritical state, thereby maximizing storage efficiency and reducing buoyancy-driven migration. Similarly, adequate porosity and permeability enhance storage capacity and injectivity, while thick and laterally continuous shale cap rocks provide effective containment by preventing upward migration of injected CO₂.

Previous geological investigations have demonstrated that depleted hydrocarbon reservoirs and deep saline aquifers within the Agbada and Akata Formations satisfy many of these geological requirements, making the Niger Delta one of the most promising sedimentary basins for geological carbon storage in sub-Saharan Africa. The geological screening criteria adopted in this study are summarized in Table 2 and provide the geological basis for interpreting the spatial suitability assessment undertaken using GIS-based multi-criteria analysis.

It should be noted that these geological parameters were not directly incorporated into the GIS weighting scheme because regional datasets describing reservoir properties (e.g., porosity, permeability, reservoir thickness, and cap-rock characteristics) are generally unavailable at continuous spatial resolution across the entire study area. Instead, the GIS-based Multi-Criteria Decision Analysis (MCDA) focused on evaluating environmental suitability and ecological sensitivity, while the published geological screening criteria were used as prerequisite conditions for identifying areas where future detailed reservoir characterization should be undertaken.

Table 2

Key Reservoir and Seal Screening Parameters for Geological CO₂ Storage in the Niger Delta Basin

S/N	Parameter	Reported values/screening criterion for the Niger Delta	Importance for CCS
1	Reservoir depth	≈ 3,000–3,500m for depleted reservoirs; >800m is accepted for supercritical CO ₂ storage	Maintains CO ₂ in a dense supercritical phase and increases storage security.
2	Porosity	10–30% in reservoirs; 27.6% measured in core samples	Determines storage capacity
3	Permeability	Approximately 130–300mD measured in core samples; values > 150mD considered favourable	Controls injectivity and pressure build-up.
4	Reservoir thickness	> 20m	Greater thickness increases storage volume.
5	Cap-rock thickness	≥ 10 m, with thick shale seals (Akata Formation) providing regional confinement	Prevents upward migration of injected CO ₂ .
6	Fault density/Structural integrity	Moderate faulting with competent reservoir-seal pairs	Faults influence leakage risk and leakage risk
Source: Ojo & Tse (2016); Mutaza et al. (2025)			

Conceptual Framework

The conceptual framework guiding this study is presented in Fig. 2. It illustrates the interactions among industrial CO₂ emission sources, carbon capture and transportation systems, geological storage reservoirs, blue ecosystem components, environmental risks, governance structures, and community perceptions.

The framework assumes that the environmental sustainability of geological carbon sequestration depends not only on geological suitability but also on ecological sensitivity, stakeholder acceptance, regulatory effectiveness, and long-term environmental monitoring. Consequently, environmentally sustainable CCS deployment requires integrating geological assessment with ecosystem-based spatial planning and participatory governance.

Questionnaire Survey

A structured questionnaire was administered to selected respondents across eleven coastal communities in Akwa Ibom and Rivers States using a simple random sampling approach. A total of 430 questionnaires were distributed, of which 420 valid responses were retrieved, representing a response rate of 97.7%. Respondents included: artisanal fishers; coastal residents; environmental advocates;

youth representatives; community leaders; other stakeholders dependent upon coastal ecosystem services. The questionnaire consisted of three major sections: demographic characteristics; awareness of Carbon Capture and Storage technology; and perceptions of environmental and socio-economic risks associated with potential CCS deployment.

Prior to the main survey, the questionnaire was reviewed by experts in environmental geoscience and environmental management to establish content validity. A pilot survey was subsequently conducted to improve clarity and eliminate ambiguous questions before final administration. Participation was voluntary, anonymous, and based on informed consent.

GIS-Based Environmental Screening for Prospective Carbon Storage Planning

A GIS-based Multi-Criteria Decision Analysis (MCDA) framework was used to conduct regional environmental screening for prospective Carbon Capture and Storage (CCS) planning. Rather than identifying geologically suitable storage reservoirs, the analysis was designed to identify areas where future CCS investigations may present lower environmental conflicts with ecologically sensitive blue ecosystems. Geological feasibility was evaluated separately using published reservoir screening criteria.

The relative importance of the evaluation criteria was determined using the Analytic Hierarchy Process (AHP) based on pairwise comparison procedures developed by Saaty (1980). Criterion weights were assigned through expert judgement informed by published CCS site-selection studies. The final Environmental Compatibility Index (ECI) index was computed as:

$$ECI = \sum_{i=1}^n W_i X_i$$

1

where: W_i is normalised weight of criterion i ; and X_i = standardised score of criterion i . The normalised criteria weight is presented in Table 3.

Table 3
Normalised Criterion Weights

S/N	Criteria	Weight
1	Ecosystem sensitivity	0.30
2	Hydrological connectivity	0.20
3	Structural stability (Fault Proximity)	0.20
4	Vegetation density	0.15
5	Soil characteristics	0.10
6	Land use	0.05

Areas exhibiting higher Environmental Screening Index values were interpreted as environmentally favourable planning zones requiring subsequent geological, geomechanical, and reservoir characterization before any CCS implementation.

It is important to emphasize that the GIS-MCDA developed in this study does not identify or validate geologically suitable CO₂ storage reservoirs. Instead, it provides a regional environmental screening framework for prospective CCS planning by identifying areas where future geological investigations may be undertaken with relatively lower potential conflicts with ecologically sensitive blue ecosystems. Confirmation of geological suitability requires detailed site-specific reservoir characterization, including petrophysical analyses, injectivity testing, cap-rock integrity assessment, geomechanical evaluation, and dynamic CO₂ storage simulations.

Spatial Overlay Analysis

Spatial overlay analysis was performed to identify areas where potential geological screening zones intersected ecologically sensitive environments. Ecological layers included: mangrove forests; estuaries; lagoons; marine protected areas; coral reef habitats; and coastal fishing grounds.

This analysis quantified the percentage of each ecological zone occurring within the identified screening areas. The resulting overlap was interpreted as indicating potential environmental interaction requiring enhanced environmental assessment, rather than evidence of actual environmental degradation.

Buffer Sensitivity Analysis

A sensitivity analysis was undertaken using 3km, 5km, and 10km buffer distances surrounding the identified geological screening zones to evaluate the robustness of the spatial interaction results. The analysis assessed whether increasing buffer distances significantly altered the relative ranking of ecological overlap. Stable rankings across buffer scenarios were interpreted as evidence that the observed spatial relationships were robust and not artifacts of a particular buffer threshold.

Statistical Analysis

Questionnaire responses were coded and analysed using IBM SPSS Statistics. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were computed to summarise respondents' awareness and perceptions.

The association between awareness of Carbon Capture and Storage and perceived environmental risk was evaluated using Pearson's Chi-square test of independence. While Binary logistic regression was employed to identify the socio-demographic and awareness-related factors influencing respondents' perceptions of environmental risks associated with Carbon Capture and Storage (CCS). The dependent variable was perceived environmental risk, coded as 1 (high risk perception) and 0 (low risk perception). Independent variables included awareness of CCS technology, knowledge of geological carbon storage, perceived adequacy of information, previous community engagement, occupation, education level, age, and gender. Odds ratios (OR) with 95% confidence intervals were computed to estimate the likelihood of high-risk perception. Statistical significance was assessed at the 5% level ($p < 0.05$).

The strength of the association was measured using Cramer's V using:

$$V = \sqrt{\frac{\chi^2}{N(k-1)}}$$

2

Where χ^2 is Chi Square; N is the sample size K is. with values interpreted as:

1. 0.10 = weak association;
2. 0.30 = moderate association;
3. 0.50 = strong association.

All statistical tests were conducted at the 99% confidence level ($p < 0.01$). Statistical findings were integrated with the GIS-derived spatial analyses to evaluate the extent to which public perceptions corresponded with environmentally sensitive areas identified through spatial analysis.

Analytic Hierarchy Process (AHP)

The relative importance of the evaluation criteria was determined using the Analytic Hierarchy Process (AHP) developed by Saaty (1980). AHP is a structured multi-criteria decision-making technique that decomposes complex decision problems into a hierarchy of criteria and determines their relative importance through pairwise comparisons.

For this study, six evaluation criteria considered essential for environmentally sustainable geological carbon sequestration were selected based on published CCS site-selection studies and expert

knowledge. These criteria comprised ecosystem sensitivity, hydrological connectivity, structural stability (fault proximity), vegetation density, soil characteristics, and land use.

The environmental criteria used in the GIS-MCDA complement, rather than replace geological screening criteria. Whereas the geological criteria evaluate the technical feasibility of long-term CO₂ storage within deep subsurface formations, the GIS criteria assess the environmental compatibility of potential storage locations by identifying areas where geological suitability may conflict with ecologically sensitive environments and blue economy resources. The combined framework therefore integrates engineering feasibility with environmental sustainability, thereby supporting more balanced site-selection decisions.

Pairwise comparisons were conducted using Saaty's nine-point preference scale, where values range from 1 (equal importance) to 9 (extreme importance). Intermediate values (2, 4, 6, and 8) were used where appropriate to represent compromise judgments. The pairwise comparison matrix (Table 4) was normalized by dividing each element by the sum of its respective column.

Table 4
Pairwise Comparison Matrix

S/N	Criteria	ES	HC	FP	VD	SC	LU
1	Ecosystem Sensitivity (ES)	1	2	2	3	4	5
2	Hydrological Connectivity (HC)	1/2	1	1	2	3	5
3	Fault Proximity (FP)	1/2	1	1	2	3	5
4	Vegetation Density (VD)	1/3	1/2	½	1	2	3
5	Soil Characteristics (SC)	1/4	1/3	1/3	1/2	1	2
6	Land Use (LU)	1/6	1/5	1/5	1/3	½	1

The normalized values were subsequently averaged across each row to obtain the priority weight of every evaluation criterion. The principal eigenvalue (λ_{max}) was computed to assess the consistency of the comparison matrix. The Consistency Index (CI) was determined as:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

3

where, λ_{max} = maximum eigenvalue, and n = number of evaluation criteria. The Consistency Ratio (CR) was subsequently calculated as:

$$CR = \frac{CI}{RI}$$

4

where RI denotes Saaty's Random Consistency Index. Following Saaty's recommendation, a consistency ratio less than 0.10 ($CR < 0.10$) was considered acceptable, indicating that the pairwise judgments were logically consistent and suitable for deriving criterion weights. The normalized criterion weights obtained from the AHP analysis were subsequently incorporated into the GIS-based Multi-Criteria Decision Analysis to generate the carbon storage suitability index. The consistency test was carried out as shown in Table 5.

Table 5
Consistency Test

S/N	Parameter	Value
1	λ_{max}	6.28
2	CI	0.056
3	RI	1.24
4	CR	0.045

Since $CR = 0.045 < 0.10$, the matrix is considered consistent.

RESULTS

A comprehensive assessment of community awareness and risk perception regarding geosequestration in the Niger Delta region was conducted through the administration of a structured questionnaire, a response rate of 97.7% was obtained. The survey targeted key stakeholders, including local residents, who responded to a set of fourteen well-designed items aimed at eliciting informed opinions and perceptions. The responses collected provide valuable insights into the prevailing level of awareness and perceived risks associated with geosequestration activities. The summarized results of this survey are presented in Table 6.

Table 6
Community Awareness and Risk Perception Survey (N = 420)

S/N	Question	Response		Percentage	
		Yes	No	Yes	No
1	Have you heard of “carbon geosequestration” before now?	18	402	4.29	95.71
2	Do you know that carbon dioxide can be stored underground in deep rock layers?	12	408	2.86	97.14
3	Has anyone ever educated your community about carbon capture and storage?	0	420	0.00	100
4	Do you know if your community is being considered as a potential carbon storage site?	0	420	0.00	100
5	Do you believe carbon geosequestration is meant to fight climate change?	21	399	5.00	95.00
6	Do you feel you have enough information about this technology to form an opinion?	18	402	4.29	95.71
7	Do you feel your community’s concerns are taken seriously by companies or government agencies	30	390	7.14	92.86
8	Do you think geosequestration could affect your fishing or farming activities?	380	40	90.48	9.52
9	Do you feel your environment is at risk if carbon is stored underground nearby?	390	30	92.86	7.14
10	Would you feel unsafe living close to a carbon storage site?	410	10	97.62	2.38
12	Would you prefer alternative climate solutions (like solar energy) instead of underground carbon storage?	420	0	100	0.00
13	Do you think more studies and public consultations should be done before implementing Geosequestration?	420	0	100	0.00
14	Would you participate in a community forum about carbon storage if invited?	412	8	98.10	1.90

The findings of the survey indicate that approximately 96% of respondents lacked prior knowledge or awareness of carbon geosequestration. Furthermore, it reveals a profound information gap within the study area concerning carbon capture and storage (CCS) technologies, including the principles, processes, and potential environmental implications associated with their deployment. A significant majority (93%) of the respondents expressed concern over the potential environmental risks associated with the siting of Carbon Capture and Storage (CCS) facilities within their blue ecosystems, indicating a high level of perceived ecological vulnerability and apprehension regarding the integration of such technologies in sensitive marine and coastal environments.

Table 7
Chi-Square of Independence test between Awareness
of Carbon Geosequestration and Environmental Risk
Perception

Low Awareness	High Risk	Low Risk	Total
	345	35	380
High Awareness	25	15	40
Total	370	50	420
$\chi^2(1) = 24.6$; $p < 0.001$ and Cramer's $V = 0.24$			

A significant association was observed between awareness of carbon geosequestration and environmental risk perception, $\chi^2(1, N = 420) = 24.6$, $p < 0.001$, Cramer's $V = 0.24$, indicating a small-to-moderate effect size.

Binary logistic regression identified several significant predictors of perceived environmental risk associated with CCS. Respondents who were aware of CCS technology were significantly less likely to perceive high environmental risk ($OR = 0.16$, $p < 0.001$). Likewise, respondents with higher educational attainment ($OR = 0.49$, $p = 0.016$) and those reporting previous government engagement regarding CCS ($OR = 0.30$, $p = 0.010$) exhibited lower levels of perceived risk. Conversely, respondents whose livelihoods depended on fishing or farming were more than four times as likely to perceive CCS as environmentally risky ($OR = 4.22$, $p < 0.001$), highlighting the importance of livelihood dependence in shaping public perceptions (Table 8).

Table 8
Results on Logistic Regression of perceived Environmental Risk Associated with CCS

S/N	Predictor	B	SE	Wald	P-Value	Odds Ratio (OR)	95% CI
1	Awareness of CCS	-1.82	0.52	12.4	< 0.001	0.16	0.06–0.42
2	Level of Education	-0.71	0.29	5.8	0.016	0.49	0.28–0.86
3	Government Engagement	-1.21	0.47	6.7	0.010	0.30	0.12–0.74
4	Fishing/Farming Dependence	1.44	0.38	14.3	< 0.001	4.22	2.01–8.86
5	Age	0.05	0.02	4.1	0.043	1.05	1.00-1.10

The integration of sedimentary basin attributes with the location and status of depleted oil fields provides critical insights for geosequestration planning. Areas exhibiting structural stability, low seismic activity, and adequate cap rock formations can be identified as priority zones for further feasibility

studies. Moreover, the spatial dataset (Table 9) forms the basis for modelling CO₂ plume migration, leakage risk, and long-term monitoring frameworks. Spatial analysis conducted over an area of approximately 42,000 km² revealed that many prospective geosequestration sites coincide with high-biodiversity zones, particularly within mangrove forests, freshwater swamps, and estuarine environments.

Table 9
Extent of Environmentally Screened Prospective CCS Planning Zones and Ecologically Sensitive Marine Areas

Layer	Description	Area Covered (km ²)
Potential Carbon Storage Zones	Sedimentary basins, depleted oil fields	42,000
Mangrove Forests	Dominant along Niger Delta	6,800
Coral Reefs	Primarily off Cross River estuary	2,100
Marine Protected Areas	Restricted Human Activities	1,200
Estuaries & Lagoons	Lagos Lagoon, Qua Iboe Estuary	5,300
Blue Economy Economic Zones	Ports, fishing grounds	12,000

Source: Derived from GIS spatial analysis conducted for this study

Figure 3 illustrates a significant spatial overlap between potential subsurface carbon storage sites and ecologically sensitive areas within the Niger Delta, suggesting a potential trade-off between climate mitigation efforts and biodiversity conservation. The trade-off shows the percentage spatial overlap between key ecologically sensitive zones and potential offshore geological CO₂ storage reservoirs in the Niger Delta. The highest coastal environment of potential overlap being the mangrove forests (29.9%), followed by marine protected areas, and estuaries and lagoons, coral reefs, marine protected areas, and coastal fishing ground (9.6%).

Table 10 is the potential trade-off between carbon storage and biodiversity and the associated risk level. Risk levels were classified based on the proportion of spatial overlap between ecological sensitivity and potential carbon storage sites.

Table 10
Potential Environmental Trade-offs Between Prospective CCS Planning Zones and Biodiversity Conservation

Ecological Zone	Total A (km ²)	Overlap with Carbon Storage Sites (km ²)	% of Zone Overlapped	Risk Level
Mangrove Forests	6,800	2,030	29.9	High
Estuaries & Lagoons	5,300	1,270	23.9	Moderate
Coral Reefs	2,100	520	24.8	High
Marine Protected Areas	1,200	310	25.8	Moderate
Coastal Fishing Grounds	12,000	1,150	9.6	Low

Source: Derived from GIS spatial analysis conducted for this study

The spatial overlay assessment revealed that approximately 30% of the high-carbon storage zone spatially coincides with biodiversity priority areas. This represents a moderate co-benefit potential, where certain areas may simultaneously support carbon storage and ecosystem conservation. However, the remaining 70% of spatial units indicate zones requiring explicit trade-off optimisation, where policy decisions must balance climate change mitigation goals with biodiversity protection. These findings highlight the importance of spatial planning in minimizing ecological conflicts. Figure 4 is the distributions of potential carbon storage sites, marine ecosystems, and conflict zones.

Table 11 presents the result of sensitivity analysis which indicate buffer variations at 3km, 5km and 10km based on 5km buffer standard.

Table 11
Result on Sensitivity analysis showing effect of Buffer Distance on overlap

S/N	Ecological Zone	Buffer %			% Change (3 to 10km)
		3km	5km	10km	
1	Mangrove Forests	24.2	29.9	35.8	+ 11.6
2	Estuaries & Lagoons	19.1	23.9	28.4	+ 9.3
3	Coral Reefs	20.5	24.8	29.7	+ 9.2
4	Marine Protected Areas	21.0	25.8	30.6	+ 9.6
5	Coastal Fishing Grounds	6.2	9.6	14.8	+ 8.6
	Average	18.2	22.8	27.9	+ 9.7

Table 10 shows a consistent increase in overlap percentages with increasing buffer distance across all ecological zones. The average overlap rises from 18.2% at 3km to 27.7% at 10km, demonstrating the expected effect of spatial expansion. Despite the increase, the relative ranking of ecological zones remains largely stable, with mangrove forests consistently exhibiting the highest overlap, and coastal fishing grounds the lowest. This indicates that the spatial distribution pattern of CCS and ecosystem interaction is robust and not highly sensitive to buffer selection. Notably, coastal fishing grounds shows a comparatively lower rate of increase, reinforcing their limited spatial interaction with carbon storage zone even under expanded buffer conditions. Table 12 is the result of relative spatial coverage relating each layer to the total carbon storage zone (42,000 km²) to determine how much of the CCS space is interacting with each system.

Table 12
Relative Coverage of Ecological Layers within Regionally Screened Prospective CCS Planning Zones

S/N	Layer	Area (Km ²)	% of Carbon Storage Zone
1	Mangrove	6,800	16.2
2	Coral Reefs	2,100	5.0
3	Marine Protected Areas	1,200	2.9
4	Estuaries and Lagoons	5,300	12.6
5	Coastal Fishing Grounds	12,000	28.6

Source: Derived from GIS spatial analysis conducted for this study

In Table 12, coastal fishing grounds account for the largest proportion of the carbon storage spatial domain (28.6%), followed by mangrove ecosystems (16.2%) and estuaries systems. Marine protected areas and coral reefs occupy relatively smaller proportions (2.9% and 5.0% respectively), reflecting their more localized distribution within the study area.

DISCUSSION

The present study demonstrates substantial spatial overlap between regionally screened prospective CCS planning zones and ecologically sensitive blue ecosystems in the Niger Delta, highlighting the need to balance climate mitigation with ecosystem conservation. Approximately 30% of the identified potential carbon storage areas coincide with ecologically important environments, particularly mangrove forests, estuaries, coral reefs, and marine protected areas.

The geological screening criteria indicate that the Niger Delta Basin possesses many of the fundamental reservoir characteristics required for geological carbon storage, including deep sedimentary successions, favourable reservoir properties, competent regional shale seals, and structurally trapped depleted hydrocarbon reservoirs. Consequently, the principal challenge identified by the present study is

not the absence of suitable geological storage formations but rather the potential environmental conflicts arising from their spatial association with ecologically sensitive blue ecosystems. This distinction highlights the importance of integrating geological feasibility assessments with ecosystem-based spatial planning during future CCS implementation. Although spatial overlap does not necessarily imply environmental degradation, it identifies locations where future carbon capture and storage (CCS) projects may require enhanced environmental assessment and monitoring. These findings support the growing recognition that ecosystem-based spatial planning should be integrated into geological carbon storage programmes to minimise ecological conflicts while advancing climate mitigation objectives (Parsons et al., 2021; Onyeka et al., 2025).

Chi-square analysis indicated a statistically significant association between awareness and environmental risk perception, suggesting that respondents with limited knowledge of CCS were more likely to perceive the technology as posing environmental risks.

The logistic regression analysis demonstrates that awareness and education substantially reduce perceived environmental risks associated with CCS. This finding supports previous studies showing that public understanding of emerging carbon management technologies improves acceptance and reduces uncertainty. In contrast, respondents whose livelihoods depend directly on marine resources perceived significantly greater environmental risks, reflecting concerns over possible impacts on fisheries, coastal ecosystems, and local livelihoods. These findings underscore the importance of targeted stakeholder engagement and risk communication strategies prior to the implementation of large-scale CCS projects.

These findings highlight the need for enhanced public awareness and stakeholder engagement to improve community understanding and acceptance of future CCS initiatives. Communities with limited knowledge of CCS were more likely to perceive higher environmental risks, suggesting that inadequate public understanding may undermine stakeholder acceptance of future projects. Similar concerns have been reported in previous studies, which emphasize that transparent communication, early stakeholder engagement, and participatory decision-making are essential for improving public confidence in emerging carbon management technologies.

The observed spatial interactions are particularly significant because the Niger Delta already experiences cumulative environmental pressures arising from decades of hydrocarbon exploitation, oil spills, coastal erosion, and habitat degradation. Consequently, introducing large-scale geological carbon storage without adequate ecological safeguards could intensify existing environmental stressors. Rather than indicating that CCS is inherently unsuitable for the region, the findings suggest that careful site selection, comprehensive environmental impact assessment, and long-term ecological monitoring should form integral components of future CCS implementation. This conclusion is consistent with international best practices advocating Strategic Environmental Assessments (SEAs), marine spatial planning, and adaptive environmental management for carbon storage projects.

Mangrove Ecosystems: A Critical Conservation Priority

Mangrove forests exhibited the highest degree of spatial overlap with prospective carbon storage zones (29.9%), making them the ecological component most likely to require careful consideration during future CCS planning. Mangroves represent globally important blue carbon ecosystems that provide shoreline stabilization, carbon sequestration, biodiversity conservation, and nursery habitats for commercially important fisheries. Their ecological integrity is already threatened by oil pollution, deforestation, and sea-level rise within the Niger Delta (O'Farrell et al., 2025). Consequently, any future geosequestration activities located near these ecosystems should be preceded by rigorous environmental baseline studies and continuous monitoring to minimise potential ecological disturbance. Protecting mangrove ecosystems would simultaneously support biodiversity conservation, climate adaptation, and the long-term sustainability of Nigeria's blue economy.

Vulnerability of Estuarine and Coral Reef Ecosystems

Estuaries, lagoons (23.9%), and coral reef ecosystems (24.8%) also exhibited considerable spatial interaction with prospective carbon storage areas. These ecosystems play fundamental roles in nutrient cycling, fisheries productivity, shoreline protection, and biodiversity conservation (Anna & Gasiokwu, 2024; Ajidahun et al., 2025). Although geological carbon storage is designed to ensure secure long-term CO₂ containment, accidental leakage or unintended hydrogeochemical changes could potentially alter local water chemistry, affecting sensitive aquatic organisms. Such risks remain largely theoretical within the Niger Delta because no commercial offshore CCS projects currently exist. Nevertheless, the identified spatial overlap highlights the importance of precautionary environmental management, including hydrogeochemical monitoring and ecosystem surveillance during future CCS deployment.

Implications for Marine Protected Areas and Environmental Governance

Approximately 25.8% of the prospective carbon storage zones intersect with designated Marine Protected Areas (MPAs), indicating potential interactions between climate mitigation initiatives and biodiversity conservation objectives. Since MPAs are established to conserve critical habitats and endangered species, future CCS developments within or adjacent to these areas should be subject to stringent environmental assessment and regulatory oversight. The findings therefore reinforce the need for a comprehensive national regulatory framework governing geological carbon storage, including environmental permitting, ecological monitoring, liability provisions, and stakeholder participation. Such measures would strengthen Nigeria's commitment to international biodiversity conservation agreements while supporting responsible carbon management.

Coastal Fishing Grounds and Community Livelihoods

The spatial interaction between prospective carbon storage zones and coastal fishing grounds (approximately 9.6% direct overlap and 25.6% within the broader assessment buffer) highlights the socio-economic dimension of future CCS planning. Artisanal fisheries constitute an essential source of food security, employment, and household income for many coastal communities. Although the present study does not demonstrate that CCS will adversely affect fisheries, it identifies areas where future

development should carefully consider potential impacts on fishing activities, marine habitat quality, and community livelihoods. These findings support previous recommendations advocating inclusive stakeholder participation, transparent risk communication, and community-based decision-making throughout the planning and implementation of carbon storage projects (O'Leary et al., 2018).

This study demonstrates that successful deployment of geological carbon storage in the Niger Delta will depend not only on favourable geological conditions but also on integrating ecological sustainability, spatial planning, and social acceptance into decision-making. The proposed geospatial framework provides a valuable decision-support tool for identifying areas where climate mitigation objectives and ecosystem conservation may converge or conflict, thereby contributing to more sustainable and environmentally responsible CCS development in Nigeria.

CONCLUSION

This study has provided a comprehensive geospatial analysis of the spatial interactions between regionally screened prospective CCS planning zones and ecologically sensitive zones in the Niger Delta region of Nigeria. Spatial analyses indicate substantial overlap between environmentally sensitive ecosystems and areas identified through regional environmental screening as environmentally compatible for future CCS investigations, subject to detailed geological and engineering characterization. These findings emphasize the importance of ecosystem-based planning and environmental safeguards during future CCS implementation. The findings underscore a delicate trade-off between advancing Nigeria's climate mitigation agenda through geosequestration and preserving its blue economy assets and coastal biodiversity. Notably, mangrove forests, which are already under threat from oil pollution and deforestation, were identified as the most significantly impacted ecosystem type.

Furthermore, the spatial conflicts exposed by the GIS overlay analysis highlight an urgent need for evidence-based spatial planning, particularly in zones where ecological vulnerability intersects with geological suitability for carbon storage. If left unaddressed, these conflicts could compromise ecosystem integrity, displace vulnerable populations, and trigger regulatory and legal challenges, ultimately undermining the sustainability of Nigeria's carbon neutrality efforts. For Nigeria to achieve a sustainable decarbonization pathway, it must recognize that climate mitigation technologies, particularly those involving the use of geological carbon storage, are not spatially neutral. This research demonstrates that without careful spatial planning, geosequestration could undermine the very ecosystems that offer natural climate solutions. Thus, a balanced and inclusive approach that integrates science, policy, and community input is essential to ensuring that carbon storage advances do not come at the expense of biodiversity, ecosystem services, or blue economy livelihoods. This study suggests that while geosequestration offers a viable path to climate change mitigation in Nigeria's Niger Delta, it must be approached with caution and balance. Integrating ecosystem-based planning and biodiversity impact assessments into the early stages of carbon storage site selection is essential to avoiding irreparable ecological damage. Adaptive governance, including community co-management models and dynamic zoning regulations, may offer pathways to reconcile these competing sustainability goals.

Therefore, a phased implementation roadmap is recommended, beginning with baseline ecological assessment, followed by pilot-scale CCS projects, stakeholder consultation, and continuous environmental monitoring. Future research should focus on long-term ecological impacts, leakage risk modelling, and socio-economic implications of CCS deployment in Tropical marine environment.

This study relied primarily on GIS-based spatial analysis and community perception surveys. Detailed reservoir characterization, injection modelling, geomechanical simulations, and leakage assessments were beyond the scope of the present investigation. Consequently, the identified potential storage zones should be regarded as preliminary areas requiring further geological and engineering investigations before actual CCS deployment.

Declarations

Conflict of Interests Declaration

The authors declare that there are no conflicts of interest regarding this manuscript. All authors have no financial, personal, or professional relationships that could be perceived as influencing the contents or interpretation of the results presented in this study.

Funding Declaration

This research received no external funding. The authors conducted the study without financial support from any public, private, or not-for-profit funding agencies. All aspects of the research, including data collection, analysis, interpretation, and manuscript preparation, were carried out solely by the authors.

Consent to Participants Declaration

Prior to participation, all respondents were informed of the purpose and nature of the study. Participation was entirely voluntary, and informed consent was obtained from all participants before the administration of questionnaires. Participants were assured of anonymity and confidentiality, and no personally identifiable information was collected. Respondents were also informed of their right to decline participation or withdraw at any point without any consequences. All data were handled securely and used strictly for academic and research purposes.

Clinical Trial Number

not applicable

Consent to Publish Declaration: not applicable

Ethical Approval and Consent to Participate

Approval for this study was granted by the Maritime Academy of Nigeria, Oron, Nigeria, through its Research Department, which serves as the institutional body responsible for reviewing and approving

research protocols in accordance with the institution's research and ethical guidelines. Given the anonymous and non-invasive nature of the survey, no personally identifiable or sensitive data were collected. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki.

Prior to participation, all respondents were adequately informed about the purpose and nature of the study, and written informed consent was obtained from each participant. Participation was entirely voluntary, and participants were informed of their right to decline participation or withdraw from the study without penalty. The anonymity and confidentiality of participants were maintained throughout the data collection, analysis, and reporting processes. All participants were adults aged 18 years and above; consequently, parental or legally authorized representative consent was not applicable.

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Author Contribution

U. E. contributed the following: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft and Resources. J. A. contributed the following: Supervision, Data curation, Validation, Resources, Writing – review & editing. B. N. contributed the following: Resources, Data curation, Project administration, Resources, Writing – review

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

References

1. Adigun P, Abah EO, Ajileye OD. Intensifying human-driven heatwaves characteristics and heat related mortality over Africa. *Environ Research: Clim.* 2024;3(1):015007.
2. Akinyem A. Yoruba Philosophy and African Metaphysics: An Introduction. University; 2010.
3. Ajidahun J, Oluwajana OA, Ifanagan AS. Structural and petrophysical assessment of CO₂ storage in depleted Z-field reservoirs, Offshore Niger Delta Basin. *Mar Georesour Geotechnol.* 2025;1:18. 10.1080/1064119x.2025.2498030.
4. Aminu MD, Nabavi SA, Rochelle CA, Manovic VA. Review of developments in carbondioxide storage. *Appl Energy.* 2017;208:389–1419. 10.1016/j.apenergy.2017.09.015.

5. Anna O, Gasiokwu PI. The concept of environmental justice in the Nigeria legal system. *Global J Politics Law Res.* 2024;12(5):27–40.
6. Benson SM, Cole DR. CO₂ sequestration in deep sedimentary formations. *Elements.* 2008;4(5):325–31. <https://doi.org/10.2113/gselements.4.5.325>.
7. Blackford JC, Jones N, Proctor R, Holt J. Regional scale impacts of distinct CO₂ additions in the North Sea. *Mar Pollut Bull.* 2009;58(10):1461–8.
8. Chabangu N, Beck B, Hicks N, Botha G, Viljoen J, Davids S, Cloete M. The investigation of CO₂ storage potential in the Zululand Basin in South Africa. *Energy Procedia.* 2014;63:2789–99.
9. Chernik PS, Caniggia M, Mitchell E. (2024). Effective communication in an emerging CCS industry: An application of the SPE SRMS to convey contingencies, uncertainties, commercially, and progress to project approval. *Front Energy Res*, 12, Article 1459830.
10. Dike EC, Amaechi CV, Beddu SB, Weje II, Ameme BG, Efeovbokhan O, Oyetunji AK. Coastal Vulnerability Index sensitivity to shoreline position and coastal elevation parameters in the Niger Delta region, Nigeria. *Sci Total Environ.* 2024;919. <https://doi.org/10.1016/j.scitotenv.2024.170830>.
11. Eggleston HS, Buendia L, Miwa T, Ngaraanabe K, editors. (2006). Institute for Global. Environmental Strategies (IGES), Hayama, Japan. Retrieved 16th April 2020 from: <http://www.ipccnggip.iges.or.jp/public/2006gl/vol4.html>
12. Eigbe PA, Ajayi OO, Olakoyejo OT, Adelaja AO. Characterization of depleted hydrocarbon reservoir AA-01 of KOKA Field in the Niger Delta Basin for sustainable Sub-Sea Carbon Dioxide Storage. *J Mar Sci Appl.* 2024;23:544–64. <https://doi.org/10.1007/s11804-024-00464-9>.
13. Evans UF, Asamudo NU, Ekanem CH. Proportionate risk-based approach to groundwater quality sustainability in the Nigerian Niger Delta. *J Environ Earth Sci.* 2014;4(12):43–8.
14. Evans UF, Ayedun F, Umoh MD, Akpabio IO. Self-potential anomalies associated with subsurface electrokinetic and electric current density coupling in parts of Southern Nigeria. *J Earth Sci Geotech Eng.* 2024;14(2):1–15. <https://doi.org/10.47260/jesge/1421>.
15. Evans GU, Evans UF, John DE. Causal modelling of marine pollutants as determinants of marine life extinction in the Nigerian coastal environment. *J Environ Water Resource.* 2014;3(8):184–91.
16. Gaspers A, Oliveira RV, Oftebro TL, Palmer E. Investigating the socio-political, acceptance of negative emission technologies: A group model building approach. *Sustainable Prod Consum*, 47, 670–81.
17. Gattuso JP, Magnan AK, Bopp L, Cheung WW, Duarte CM, Hinkel J, Mcleod E, Micheli F, Oschlies A, Williamson P, Billé R. Ocean solutions to address climate change and its effects on marine ecosystems. *Front Mar Sci.* 2028;5:337.
18. Ghafouri B. Fairness in climate change mitigation: The case of carbon taxation. *Am J Clim Change.* 2023;12(4):548–78. 10.4236/ajcc.2023.124025.
19. Guild R, Wang XX, Quijon X. Climate change impacts on coastal ecosystems. *Environ Research: Clim.* 2025;3(4). 10.1088/2752/ad9f90.

20. House KZ, Schrag DP, Harvey CF, Lackner KS. (2009). Permanent carbon dioxide storage in deep-sea sediments. *Proceedings of the National Academy of Sciences*, 103(33), 12291–12295.
21. Ibeabuchi U. Mapping carbon storage and sequestration in Nigeria: A REDD Policy Initiatives. *Water Environ Sustain*. 2023;3(3):11–29.
22. International Energy Agency. *World Energy Outlook 2021*. Paris, France: IEA; 2021.
23. Intergovernmental Panel on Climate Change. *Climate Change 2022: Mitigation of Climate Change*. Cambridge University Press; 2022.
24. IEA. (2021). *World Energy Outlook*, International Conference and Exhibition, Lagos, Nigeria, August 2022. <https://doi.org/10.2118/211986-MS>
25. IPCC. *Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*. Prepared by the National Greenhouse Gas Inventories Programme.
26. Jayeola I, Olusola B. (2022). Evaluating Injectivity Index of Niger Delta Reservoirs for CO₂ Geological Sequestration. Paper presented at the SPE Nigeria Annual.
27. Katsanevakis S, Coll M, Fraschetti S, Giakoumi S, Goldsborough D, Mačić V, Mackelworth P, Rilov G, Stelzenmüller V, Albano PG, Bates AE. (2020). Twelve recommendations for advancing marine conservation in European and contiguous seas. *Frontiers in Marine Science*, 7, 565968, 2020.
28. Leung D, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. *Renew Sustain Energy Rev*. 2014;9:426–43.
29. Li C, Zhao X, Duan W, Wu T, Yao Z, Chen G, Li G, Peng X. (2022) Strategic and geodynamic analyses of geosequestration of CO₂ in China offshore sedimentary basins. *Chinese Journal of Theoretical and Applied Mechanics*, 55: 719–731. 10.6052/0459-1879-22-384, 2022.
30. Mollicone DF, Achard S, Federici H, Eva G, Grassi A, Belward F, Raes G, Seufert H, Stibig G, Matteucci E, Schulze D. (2007). An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. *Climatic Change* 83: 477–493. <https://doi.org/10.1007/s10584-006-9231-2>, 2007.
31. Mutadza T, Ikiensikimama SS, Joel OF. Geo-mechanical and geomorphology characterisation of the cap rocks in the Niger Delta for potential CCS. *Heliyon*. 2024;10:e31206. <https://doi.org/10.1016/j.heliyon.2024.e31206>.
32. Mutadza I, Ikiensikimama SS, Joel OF. Preliminary Assessment of the Reservoir Rock in the Niger Delta for Carbon Capture and Storage in Depleted Reservoirs. *J GeoEnergy*. 2025. <https://doi.org/10.1155/jge5/4230897>.
33. Nwozor A. Depoliticizing environmental degradation: revisiting the UNEP environmental assessment of Ogoniland in Nigeria's Niger Delta region. *Geol J*. 2020;85(3):883–900.
34. O'Farrell J, O'Fionnagáin D, Babatunde AO, Geever M, Codyre P, Murphy PC, Spillane C, Golden A. (2025). Quantifying the impact of crude oil spills on the mangrove ecosystem in the Niger Delta using AI and Earth observation. *Remote Sensing*, 17(3), 358. <https://doi.org/10.3390/rs17030358>, 2025.

35. Okiwelu A, Evans U, Obianwu V. Geoelectrical investigation of external corrosion of earth buried pipeline in the coastal area of Gulf of Guinea. *J Am Sci*. 2011;7(8):221–6.
36. O’Leary BC, Ban NC, Fernandez M, Friedlander AM, Borboroglu PG, Golbuu Y, Guidetti P, Harris JM, Hawkins JP, Langlois T, McCauley DJ, Kikitch EK, Richmond RH, Robert CM. Addressing criticisms of large-scale marine protected Areas. *Bioscience*. 2024;68(5):359–70.
37. Omefe V, Marvin MK, Sarkinbaka ZM, Fagorite VI, Ngulde AB. (2025). Prospect studies and geological CO₂ storage potential in Nigeria. *Unconventional Resources*, 7. Available at <https://doi.org/org/10.1016/j.juncres.2025.100206>
38. Ogbo OG, Onuoha DC, Odoh CC. (2024). Carbon capture and storage (CCS) in nigeria: a review of challenges and opportunities. *British Journal of Multidisciplinary and Advanced Studies* 5(4):1–18. 10.37745/bjmas.2022.04148, 2024.
39. Ojo AC, Tse AC. Geological Characterisation of Depleted Oil and Gas Reservoirs for Carbon Sequestration Potentials in a Field in the Niger Delta, Nigeria. *J Appl Sci Environ Manage*. 2016;4(1):45–55.
40. Parsons M, Taylor L, Crease R. Indigenous Environmental Justice within Marine Ecosystems: A Systematic Review of the Literature on Indigenous Peoples’ Involvement in Marine Governance and Management. *Sustainability*. 2021;13(8):4217. <https://doi.org/10.3390/su13084217>.
41. Roberts CM, O’Leary BC, McCauley DJ et al. (2017). Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences*, 114(24), 6167–6175.
42. Sam K, Zabbey N, Gbaa ND, Ezurike JC, Okoro CM. Towards a framework for mangrove restoration and conservation in Nigeria. *Reg Stud Mar Sci*. 2024;66. <https://doi.org/10.1016/j.rsma.2023.103154>.
43. Schlosberg D. *Defining Environmental Justice: Theories, Movements, and Nature*. Oxford: University; 2007.
44. Shaughnessy AR, Gu X, Wen T, Brantley SL. Machine learning deciphers CO₂ sequestration and subsurface flow paths from stream chemistry. *Hydrol Earth Syst Sci*. 2021;25:3397–409. <https://doi.org/10.5194/hess-25-3397>.
45. Sonawane MS. Types and methods of carbon sequestration: A review. *Int Archive Appl Sci Technol*. 2018;9(1):75–81.
46. Sun X, Shang A, Wu P, Liu T, Li Y. A Review of CO₂ Marine Geological Sequestration. *Processes*. 2023;11(7):2206. <https://doi.org/10.3390/pr11072206>.
47. United Nations Environment Programme. *Environmental Assessment of Ogoniland*. Nairobi, Kenya: UNEP; 2011.
48. UNEP. *Emerging Issues in Our Global Environment*. UNEP/Earthprint. 2021;9280731017:978928073101979pages.
49. Uche IU. (2023). Mangroves of the Niger Delta. In Orlex Baylen Yllano, editor, *Mangrove Biology, Ecosystem, and Conservation*. 10.5772/intechopen.109296

50. United States Environmental Protection Agency (USEPA). (2017). Causes of climate change. EPA. Retrieved August 27, 2025, from https://19january2017snapshot.epa.gov/climate-change-science/causes-climate-change_.html

Figures

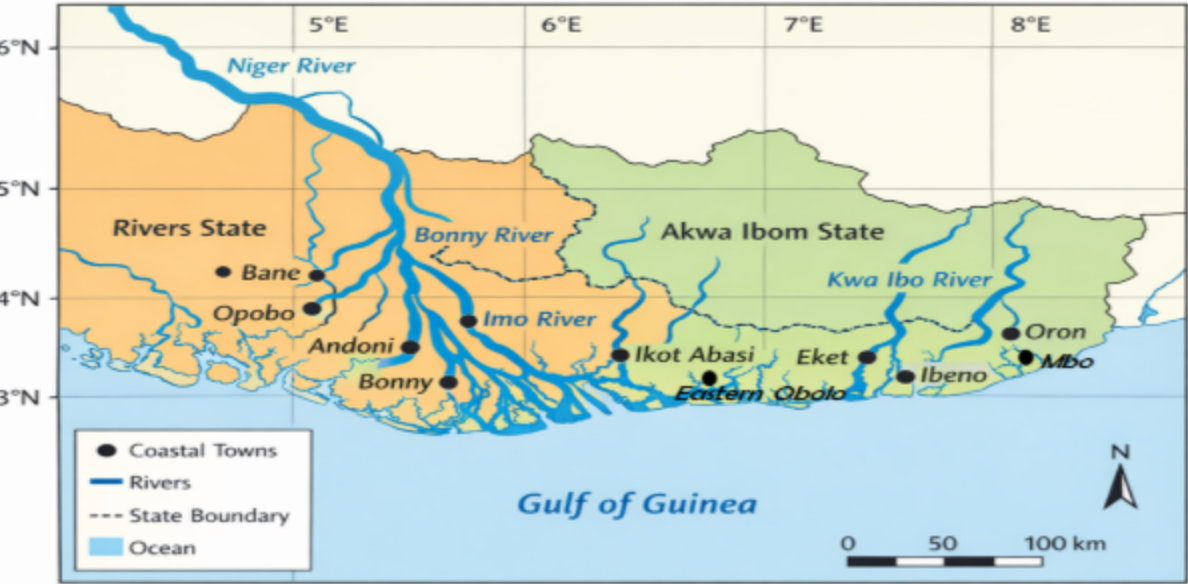


Figure 1
Map of the Study Area showing towns and Rivers in Akwa Ibom and Rivers States



Figure 1
Map of the Study Area showing towns and Rivers in Akwa Ibom and Rivers States



Figure 1

Map of the Study Area showing towns and Rivers in Akwa Ibom and Rivers States



Figure 1

Map of the Study Area showing towns and Rivers in Akwa Ibom and Rivers States

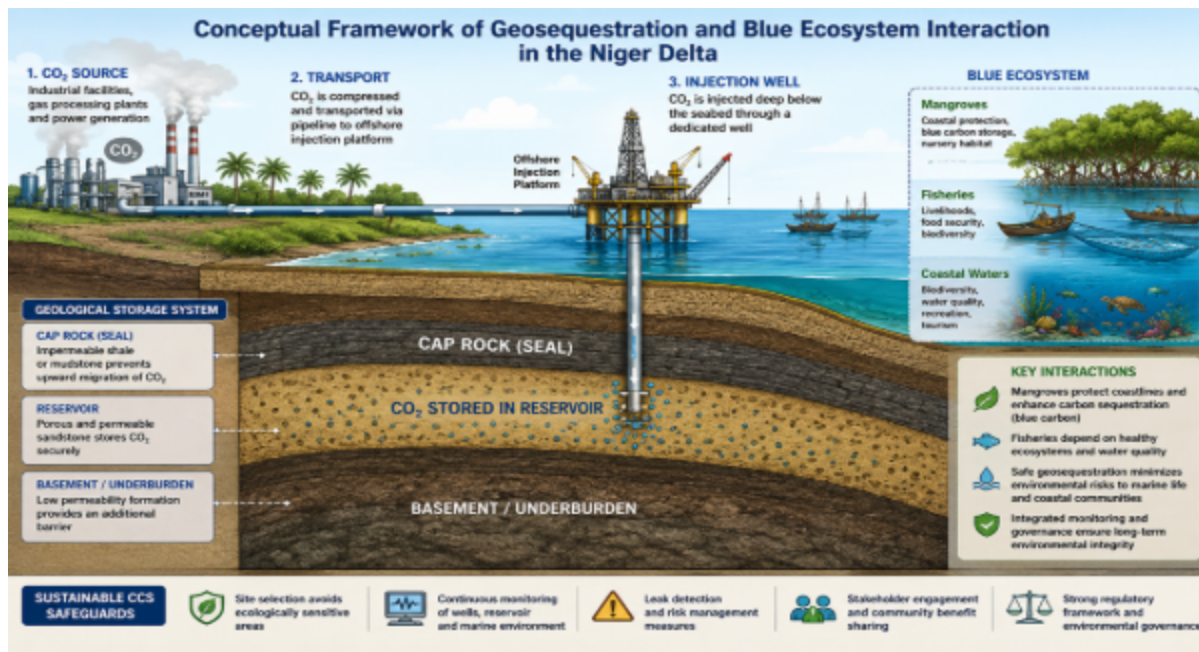


Figure 2

Conceptual framework illustrating the interactions between CO₂ geosequestration processes and blue ecosystem components in the Niger Delta, including CO₂ sources, transport pathways, injection wells, geological storage reservoirs, cap rocks, mangrove ecosystems, fisheries, and coastal waters.

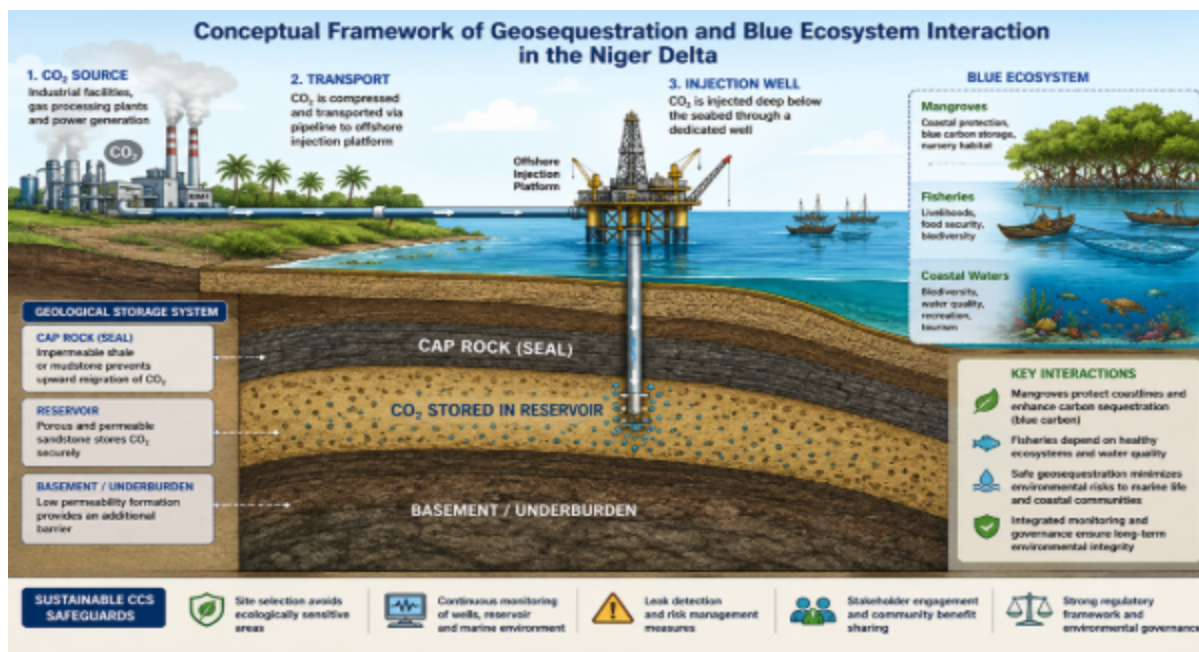


Figure 2

Conceptual framework illustrating the interactions between CO₂ geosequestration processes and blue ecosystem components in the Niger Delta, including CO₂ sources, transport pathways, injection wells, geological storage reservoirs, cap rocks, mangrove ecosystems, fisheries, and coastal waters.

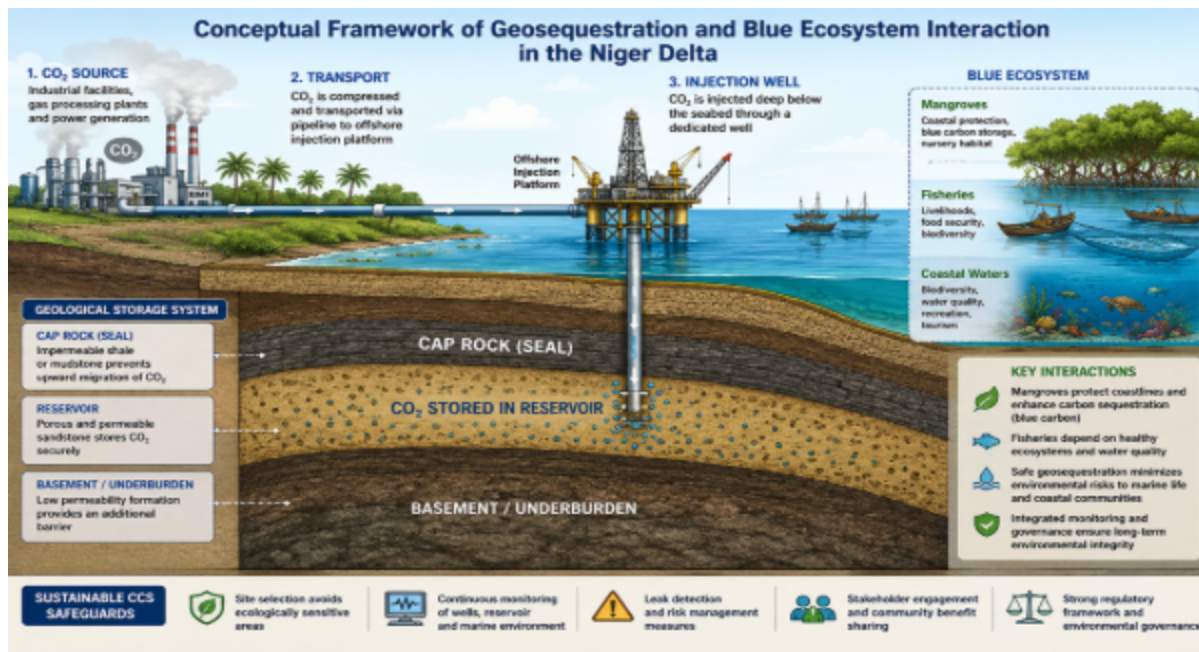


Figure 2

Conceptual framework illustrating the interactions between CO₂ geosequestration processes and blue ecosystem components in the Niger Delta, including CO₂ sources, transport pathways, injection wells, geological storage reservoirs, cap rocks, mangrove ecosystems, fisheries, and coastal waters.

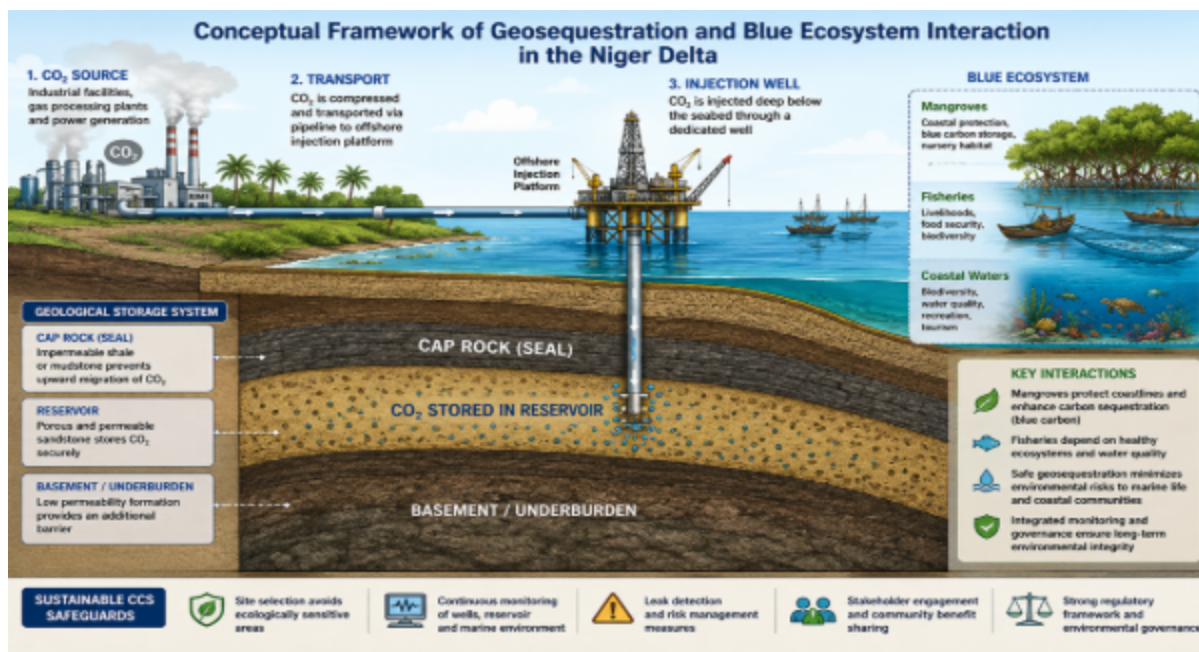


Figure 2

Conceptual framework illustrating the interactions between CO₂ geosequestration processes and blue ecosystem components in the Niger Delta, including CO₂ sources, transport pathways, injection wells, geological storage reservoirs, cap rocks, mangrove ecosystems, fisheries, and coastal waters.

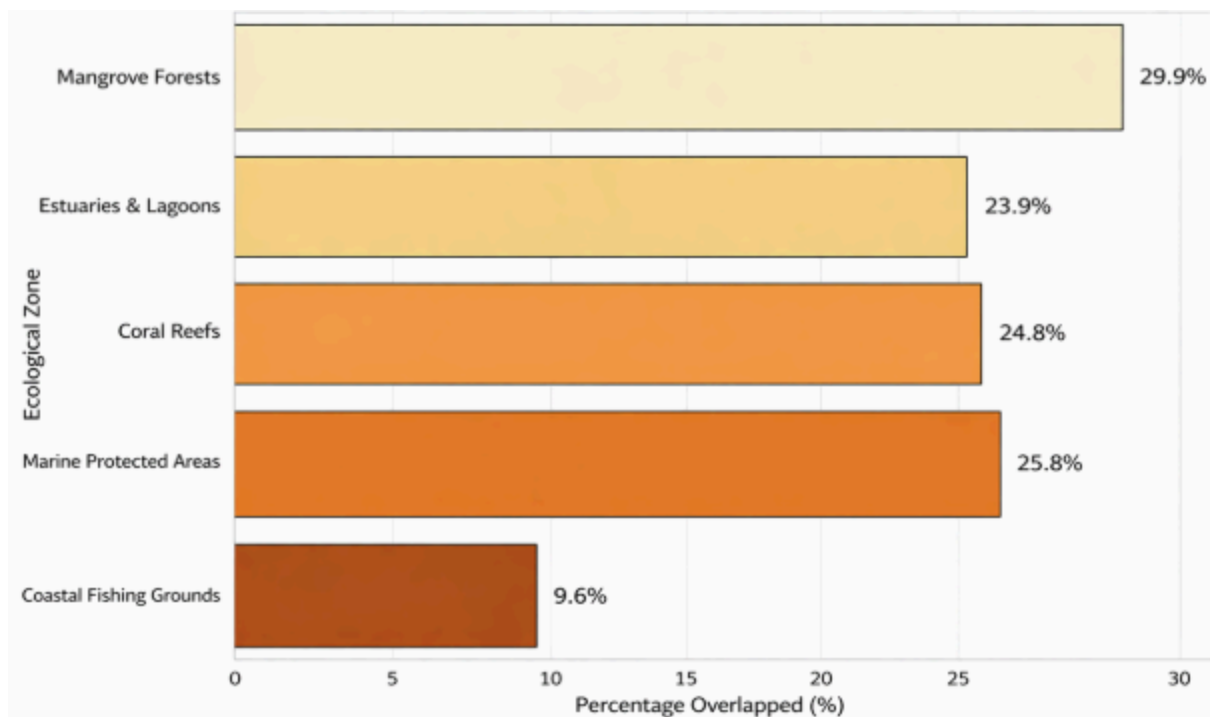


Figure 3

Percentage Overlap Between Ecologically Sensitive Zones and Regionally Screened Prospective CCS Planning Zones

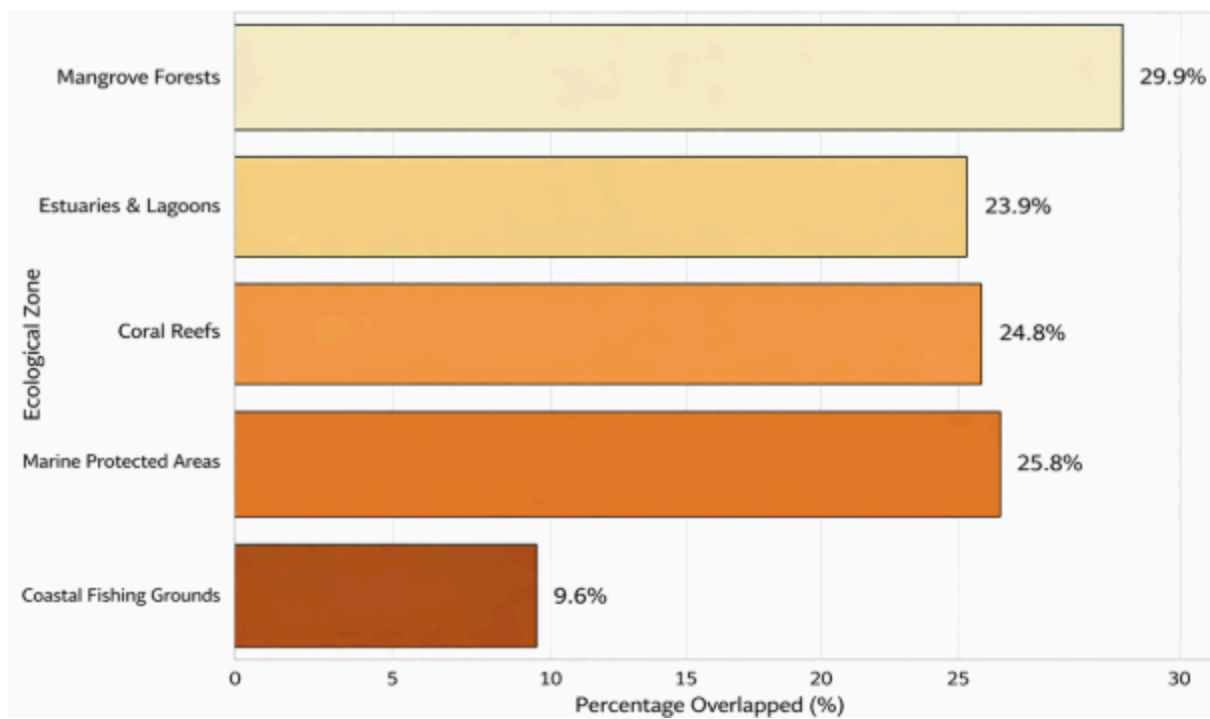


Figure 3

Percentage Overlap Between Ecologically Sensitive Zones and Regionally Screened Prospective CCS Planning Zones

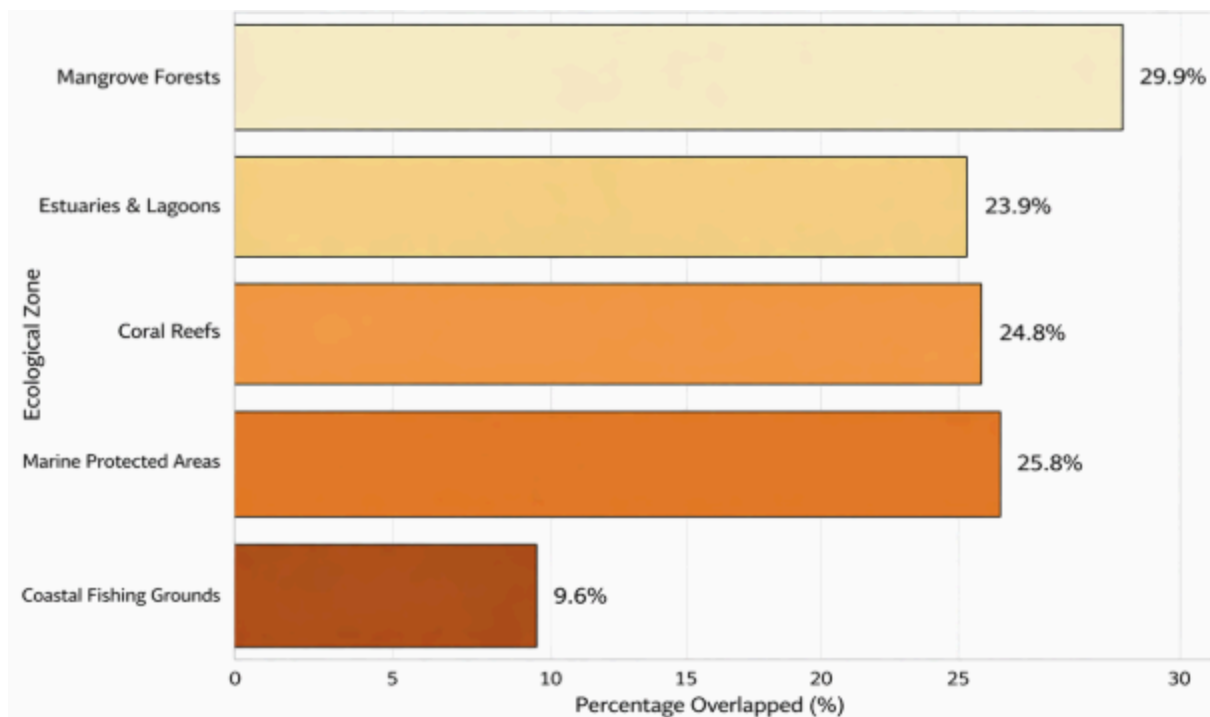


Figure 3

Percentage Overlap Between Ecologically Sensitive Zones and Regionally Screened Prospective CCS Planning Zones

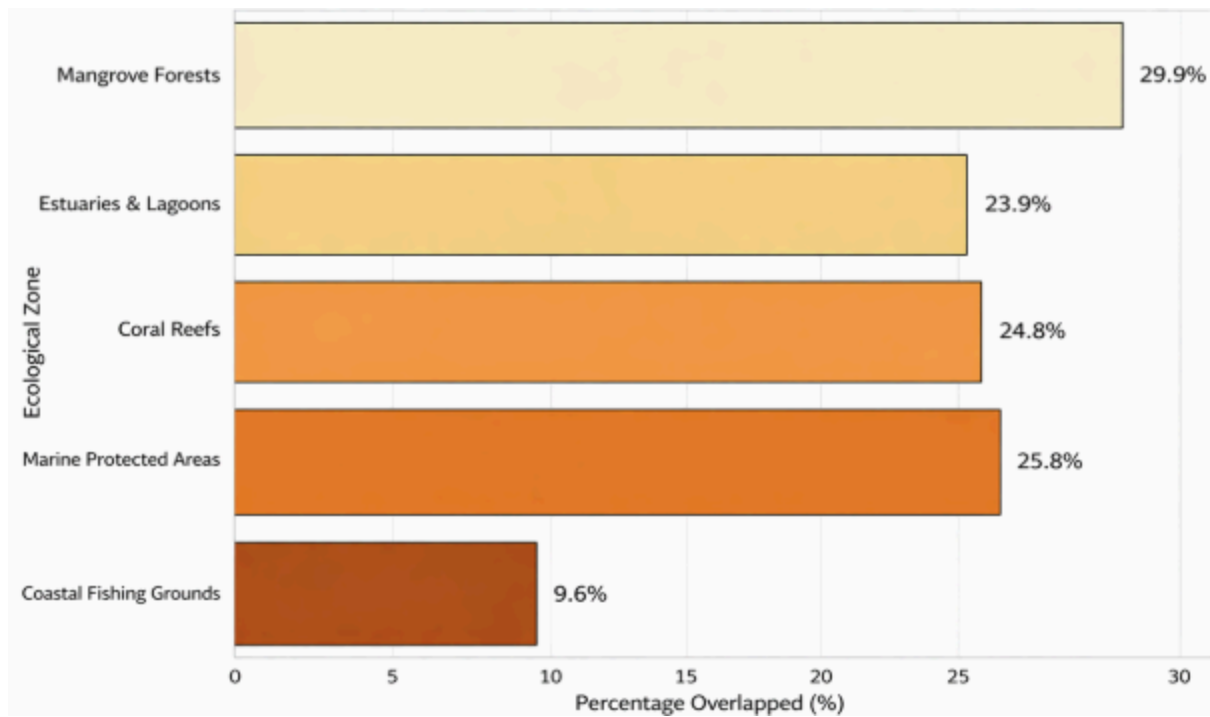


Figure 3

Percentage Overlap Between Ecologically Sensitive Zones and Regionally Screened Prospective CCS Planning Zones

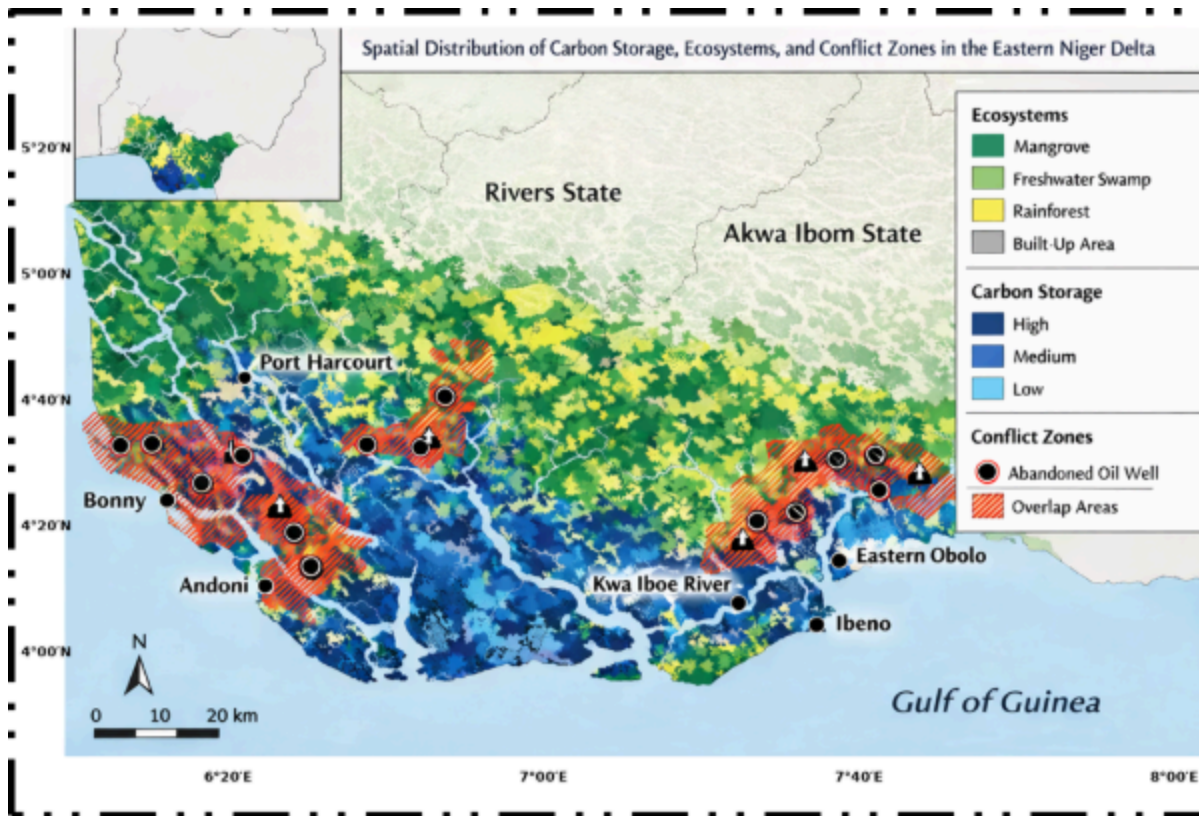


Figure 4

Spatial Distribution of Regionally Screened Prospective CCS Planning Zones and Ecological Conflict Areas

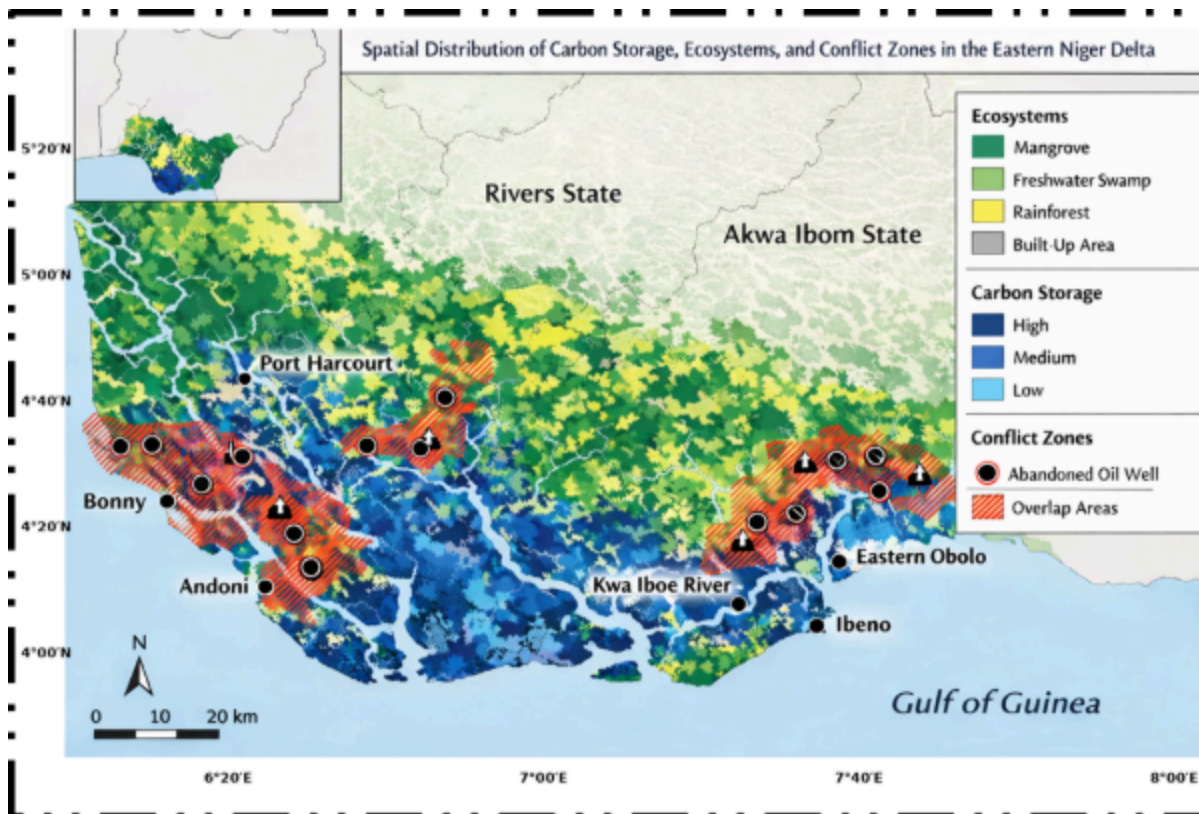


Figure 4

Spatial Distribution of Regionally Screened Prospective CCS Planning Zones and Ecological Conflict Areas

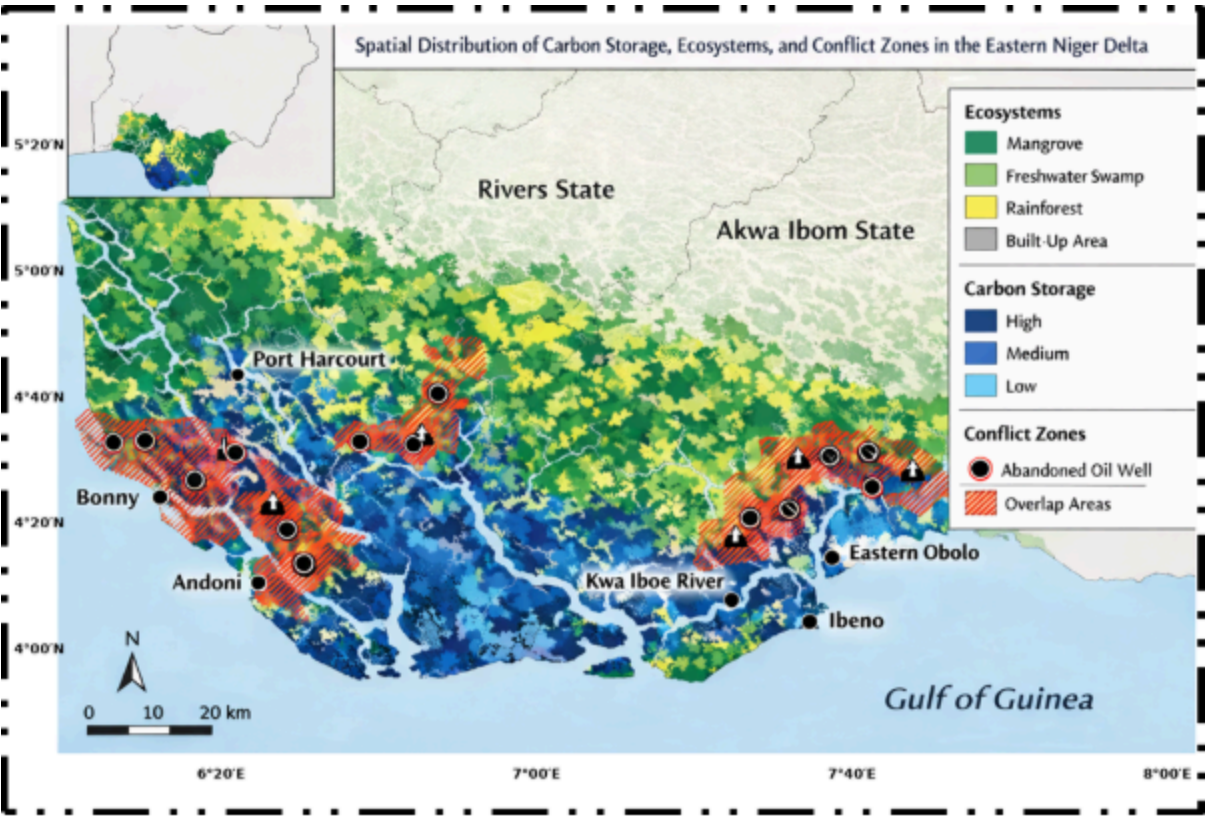


Figure 4

Spatial Distribution of Regionally Screened Prospective CCS Planning Zones and Ecological Conflict Areas

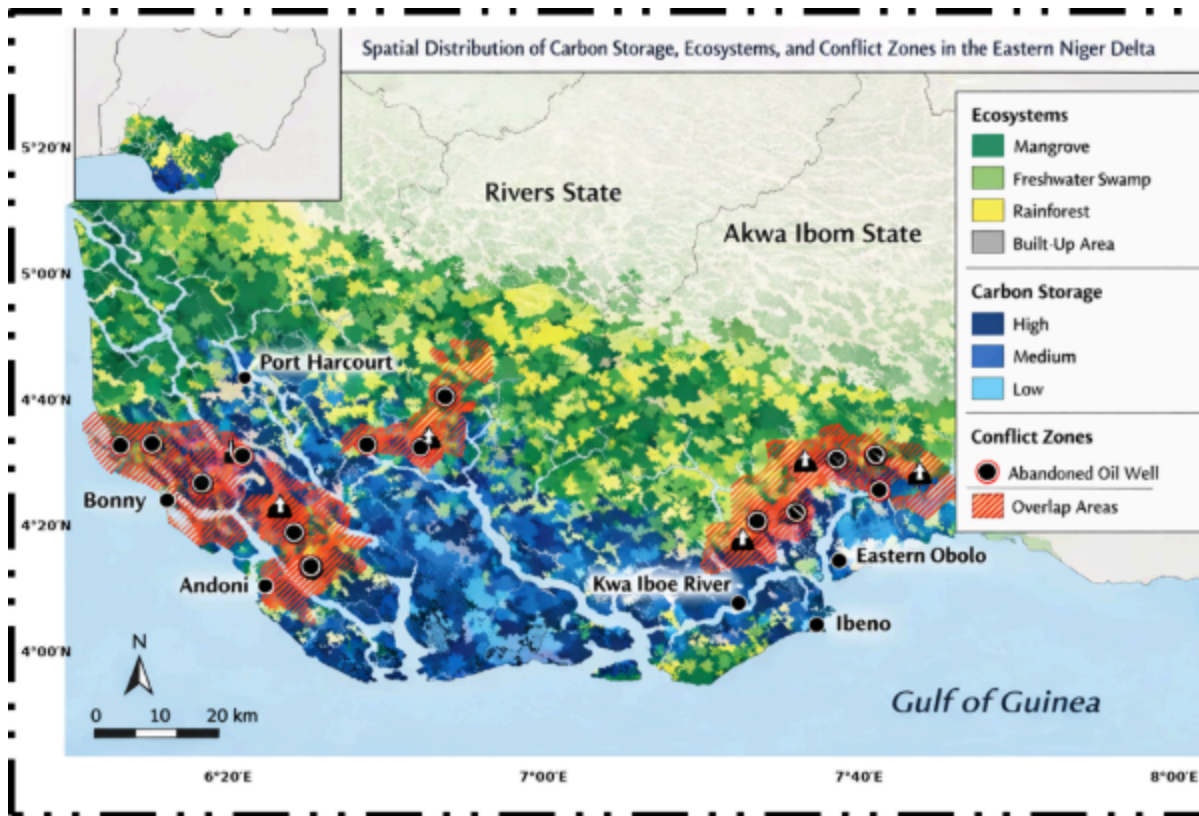


Figure 4

Spatial Distribution of Regionally Screened Prospective CCS Planning Zones and Ecological Conflict Areas