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Coastal Erosion and Sea Level Rise in Louisiana: A Critical Analysis of the Challenges, Impacts, and Mitigation Strategies

Yaw Adu Twumasi[1]*, Edmund Chukwudi Merem[2], Zhu Hua Ning[1], Harriet Boatemaa Yeboah[3], Priscilla Mawuena Loh[1], Jeff Dacosta Osei[1], Abena Boatemaa Asare-Ansah[4], Vanessa Ferchaud[1], Olipa Simon[5]

[1]Department of Urban Forestry, Environment and Natural Resources, Southern University and A & M College, Baton Rouge, LA, USA
[2]Department of Urban and Regional Planning, Jackson State University, Jackson, MS, USA
[3]Department of Geography and Tourism Studies, Brock University, St. Catharines, Canada
[4]Department of Geographical Science, University of Maryland, College Park, MD, USA
[5]Institute of Resource Assessment, University of Dar es Salaam, Dar es Salaam, Tanzania
Email: *yaw.twumasi@sus.edu, *yaw.twumasi@gmail.com

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Abstract

Louisiana faces significant environmental challenges due to coastal erosion and rising sea levels, driven by both natural processes and human activities, which threaten its ecosystems, infrastructure, and communities, necessitating a comprehensive approach to mitigation and adaptation. This paper analyzes the environmental and socioeconomic consequences of coastal land loss and sea level rise in Louisiana. Using secondary data from 1932 to 2016, the study documents significant wetland degradation, which correlates with population decline and poses substantial economic risks to the state's key industries. This study also incorporated statistical and regression analysis drawn from external datasets to compare the land loss estimates with population changes across the coastal parishes of Louisiana. While wetland losses can impact population patterns, repeated natural disasters and disruptions to key economic sectors such as oil and gas industries, shrimp and fisheries have made many coastal parishes unhabitable further contributing to population decline. Hurricanes Katrina and Rita caused the destruction of over 217 square miles of coastal wetlands, surpassing the wetland loss expected for the entire state over the next 20 years. Notably, there is an average population growth decline of 6.12% and an estimated loss of 1016 people for every hectare of wetland lost. Despite significant investments in levees and restoration projects, the risk of continued population decline remains high, with losses potentially reaching billions of dollars by 2050. The study recommends that coordinated action is needed to restore wetlands, improve infrastructure, and implement climate policies to protect the coast and ensure long-term resilience.

Keywords

Hurricane, Land Loss, Restoration, Population Decline, Wetlands

1. Introduction

Coastal regions worldwide, including those in the United States, face increasing pressure from both natural processes and human activities. The impacts of coastal erosion, rising sea levels, and land subsidence, coupled with population growth and development, are contributing to the degradation of vital coastal ecosystems. Particularly, Louisiana has experienced significant coastal land loss, and while some of this land loss can be attributed to human activities, a significant portion is due to natural forces such as land subsidence caused by sediment compaction in the Mississippi River Delta and frequent powerful storms that occur every five years [1]. Louisiana is located on the northern edge of the Gulf Coast geosyncline, which began forming in the Lower Cretaceous and has been an active site of deposition since. Located along the Gulf of Mexico in the southeastern United States, Louisiana's coastal regions are defined by extensive marshlands, wetlands, and low-lying terrain. This distinctive geographical setting exposes the state to significant vulnerabilities resulting from the adverse effects of coastal erosion and sea level rise [2] [3]. Importantly, these challenges are compounded by many natural and human-induced factors, leading to a complex web of ecological, socio-economic, and infrastructural repercussions [4].

Consequently, Louisiana bears the unfortunate distinction of experiencing one of the highest rates of coastal erosion in the United States. Over the last century, the state has observed the disappearance of approximately 1800 square miles of land [5]. Furthermore, the construction of river levees and navigation channels has resulted in a reduction of sediment supply, which would otherwise serve to replenish the coastline, thereby contributing to erosion [3] [6]. In addition to grappling with the challenge of coastal erosion, Louisiana must contend with the implications of sea level rise, a direct consequence of global climate change. Projections indicate that sea levels are set to rise at an accelerated pace, thereby exacerbating the challenges posed by coastal erosion [7] [8]. This increase in sea levels amplifies the risks faced by coastal communities and ecosystems, heightening the vulnerability of low-lying areas [8].

Rapid relative sea level rise also leads to the submergence of coastal wetlands and increases carbon mineralization. While this rise could promote carbon accumulation if more space becomes available, it may be restricted by the reduced sediment supply from the Mississippi River [9]. Additionally, hurricanes have significantly contributed to the erosion of Louisiana's barrier islands, accounting for up to 90% of shoreline retreat over the past 102 years. Since 1901, 55 hurricanes or tropical storms have hit the Louisiana coast, primarily in September, with the south-central and southwest regions experiencing the most landfalls. For instance, major storms such as Hurricane Katrina in 2005 and Hurricane Ida in 2021 had devastating impacts on communities including New Orleans (30.07˚N, 89.93˚W), Grand Isle (29.25˚N, 90.00˚W), and Houma (29.60˚N, 90.72˚W), resulting in widespread infrastructure destruction and ecosystem collapse [10] [11]. Considering the degree of damage that is caused during hurricanes, flooding and erosion events, New Orleans for instance has still not made full recovery from these events [12].

While hurricanes have caused severe erosion, they have also contributed to sediment deposition on some of Louisiana's marshes. As a result, the state's barrier islands are highly vulnerable to ongoing erosion and land loss [13]. Significantly, erosion, flooding, and the impact of the oil industry are also threatening the survival of indigenous villages like Pointe-au-Chien and Isle de Jean Charles in Louisiana. The oil industry has caused environmental damage through canals that lead to erosion and saltwater intrusion, while its contribution to climate change worsens sea level rise. This, along with the destruction of local shrimp and fish industries, is making the area uninhabitable. Displacement has already begun, with Isle de Jean Charles losing many homes between 2002 and 2012 [14]. The Mississippi River delta plain is experiencing barrier shoreface retreat due to a significant sediment budget deficit, high rates of relative sea-level rise (~0.9 cm/year), and erosion caused by storm-induced currents and waves [15].

More so, the state's barrier islands, which help protect estuaries, wetlands, salt marshes and create an estuarine system, are rapidly disappearing, shrinking by 41% from 37 mi^2 to 22 mi^2 between 1898 and 1978. These islands are migrating landward at rates of up to 65 feet per year. The life expectancy of barrier islands ranges from 30 years for the Isles Dernieres to 225 years for the Chandeleur Islands. Louisiana's barrier islands, which protect estuaries and wetlands from ocean waves and currents, are eroding rapidly at rates of up to 20 meters per year. As a result, some of these islands may disappear by the end of the century [16]. According to a recent U.S. Geological Survey atlas, these islands have lost over 40 percent of their area in the past century, with some, like the Isles Dernieres, losing up to 75 percent. Subsequently, the loss of barrier islands will lead to the destruction of estuaries, lagoons, destroying coastal wetlands, and further degradation of salt marshes if large-scale restoration efforts are not implemented. That is, if this trend continues, an estimated 4000 square kilometers could disappear within the next 50 years, significantly affecting the state's economy and increasing flood risks for New Orleans and nearby urban areas [17].

Managing current canals, preventing new ones, and redesigning canals for more natural water flow could help reduce the rate of erosion [18]. Coastal regions, including the Great Lakes, are home to over 138 million people, representing 53 percent of the U.S. population, who primarily use these areas for recreation, transportation, energy extraction and transmission, and waste disposal. Additionally, barrier islands, estuaries, and coastal wetlands serve as crucial habitats for wildlife and support commercial fisheries [17]. Preserving, enhancing, and restoring wetlands requires a variety of approaches to maintain their crucial functions.

While sea-level rise poses a significant threat to wetlands, human activities that contribute to wetland loss can be mitigated or reversed. Although the natural process of sea-level rise cannot be controlled, there is a need to focus on addressing the factors that can be influenced by man [19]. Over the past two decades, various restoration strategies have been implemented with mixed results. For instance, flood and navigation control structures halted restoration processes by confining the river's flow and diverting sediments away from the coast, leaving the wetlands without the material needed to counteract subsidence and erosion, and causing them to experience rapid disappearance.

Admittedly, some strategies were effective only under specific conditions, while others proved highly successful across a range of situations. Among the most consistently effective projects are barrier island restoration, marsh creation and enhancement, shoreline protection, and river diversions [20]. Nonetheless, a crucial issue remains in terms of assessing the effectiveness, feasibility, and long-term viability of these strategies when it comes to addressing the intricate challenges posed by coastal erosion and increasing sea levels. There is an immediate need for an exhaustive comprehension of these matters to guide policy decisions based on evidence and to enhance the resilience of Louisiana's coastal regions. Despite endeavors to implement strategies such as levees, the restoration of marshes, and the establishment of barrier islands, thorough evaluations of their efficacy and the trade-offs associated with these approaches are imperative for guiding future decision-making. The assessment of the efficiency and enduring viability of various mitigation and adaptation strategies represents a crucial gap in knowledge, and this study will specifically focus on addressing this gap.

Therefore, the primary aim of this study is to explore the complexities surrounding coastal erosion and rising sea levels in Louisiana, while scrutinizing the challenges, consequences, and approaches for mitigation. This inquiry holds significance not only at the regional level but also provides valuable perspectives on broader global concerns linked to climate change, the resilience of coastal areas, and sustainable adaptation. The research encompasses four distinct objectives: 1) ascertaining the current rate of coastal erosion in significant coastal regions of Louisiana, 2) evaluating the near-term and anticipated repercussions of rising sea levels on susceptible communities and critical infrastructure within the state, 3) assessing the efficiency of prevailing mitigation techniques, including strategies like levees and projects aimed at coastal restoration, and 4) identifying cost-efficient and sustainable methods for mitigating the challenges posed by coastal erosion and sea level rise in Louisiana. These outlined research objectives will offer a precise and targeted pathway for examining the crucial concerns associated with coastal erosion and the rise in sea levels in Louisiana.

2. Data and Methods

2.1. Study Area

Coastal Louisiana, **Figure 1**, located between approximately 29˚N to 31˚N latitudes and 89˚W to 93˚W longitudes, is one of the most critical study areas in the United States for analyzing the effects of coastal erosion, sea level rise, and extreme weather events. Louisiana's parishes are situated in the Mississippi River delta, which has the second largest river basin in the world, and like other river deltas and coastlines, is a diverse and dynamic region with areas of historical land gain and loss [21]. This includes highly vulnerable parishes such as Plaquemines, Jefferson, Terrebonne, Lafourche, and St. Bernard, all of which lie along the Gulf of Mexico. The coastal region of Louisiana has the fastest erosion rate of any coastal area in the world [1].

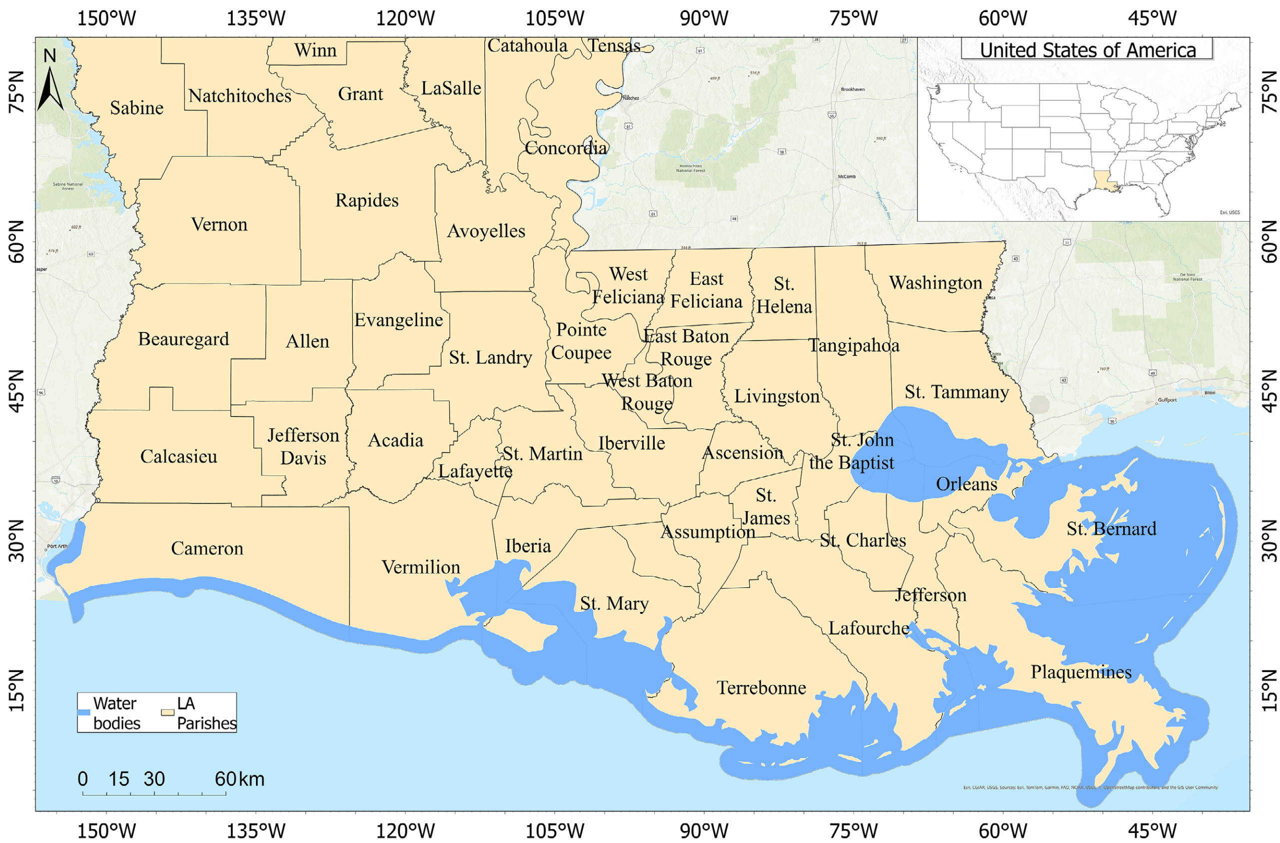

Figure 1. Map of coastal Louisiana.

Since the 1930s, coastal Louisiana has lost more than 2000 square miles of land, a phenomenon driven largely by the disruption of sediment delivery from the Mississippi River, land subsidence, and increasing wave energy [22]. Human interventions such as levee construction, oil and gas extraction, and navigation canals have significantly altered the natural hydrology and sediment flow of the delta [23]. The construction of levees has prevented the seasonal flooding necessary to deposit sediment that would otherwise sustain and rebuild the wetlands [24]. According to [25], sea levels along the Louisiana coast are rising at an average rate of 9.24 mm per year due to a combination of global sea level rise and subsidence of the soft deltaic soils. This accelerated rate of sea level rise increases saltwater intrusion into freshwater marshes, damages vegetation, and contributes to further erosion [26].

2.2. Data Sources

The study used secondary data from various sources to analyze wetland loss and its impact on coastal Louisiana. Firstly, data on population changes across Louisiana's coastal parishes were compared to wetland loss figures to understand the social impact of land degradation. Key datasets included population decline linked to wetland loss [27], measurements of sea level rise, flood risk levels across parishes (Coastal Protection and Restoration Authority), and detailed land loss and change rates. Additionally, the economic impacts of disruptions to the oil, gas, transportation, and fishing industries were assessed, highlighting significant financial and employment losses tied to environmental changes and infrastructure vulnerabilities [28]. The study also accounted for various environmental factors such as river flow, tides, and the impact of hurricanes, particularly Hurricanes Katrina and Rita, which caused extensive damage to coastal wetlands. The study also incorporated historical data, such as land loss estimates and satellite-based land area estimates for 2016, which showed a slight increase of 16 square miles over 2010. Finally, data on storm surge flood risks and wetland loss were used to project future risks for coastal parishes.

2.3. Data Analysis

This study further highlights the importance of ongoing mitigation efforts to address the growing threat of coastal erosion and related economic instability. Population data were first analyzed to estimate how the population of each parish would have evolved without the associated wetland loss, identifying the extent of the wetland loss's impact on local communities. To investigate the long-term trend of wetland loss in Louisiana, statistical analysis was conducted on the 21 observations of land area change between 1932 and 2016 from a study by [27]. The regression and counterfactual analyses presented were drawn from and summarized based on the results reported in the cited sources. The analysis incorporated both mean changes in population and direct population loss per hectare of wetland lost across different parishes, with a focus on those most impacted, such as Orleans, Jefferson, and St. Tammany parishes. An economic analysis also estimated the financial impact of frequent disruptions to Louisiana's coastal regions, with sales and earnings losses quantified under different disruption frequency scenarios. Additionally, a computer model was used to simulate potential errors in the satellite-based land area estimates, revealing that, despite a slight increase in land area between 2010 and 2016, a margin of error indicated a net decline of 151 square kilometers (58 square miles) over that period. The analysis also employed sea level rise data around Grand Isle, Louisiana, and related flood risk data based on potential disruptions due to coastal erosion, wetland loss, and storm surges. By utilizing 21 observations of land area changes between 1932 and 2016, this study assessed the trend of wetland loss in coastal Louisiana by [27].

3. Results

3.1. Wetland Loss in Coastal Louisiana and Population Decline

Table 1 shows the relationship between wetland loss and population changes in various parishes. It presents the mean change in population growth per hectare of lost wetland, as well as the mean population loss per hectare of wetland lost for each parish. The data highlight a strong negative correlation between wetland loss and population changes, with the most significant impacts seen in Orleans, Jefferson, and St. Tammany parishes. For instance, Orleans Parish experiences the largest population loss, with a mean change in population growth of −11.59 percentage points per hectare of lost wetland, translating to a population loss of 9252 people per hectare. Similarly, Jefferson and St. Tammany parishes show severe impacts, with mean losses of 887 and 1377 people per hectare, respectively.

Table 1. Wetland loss in coastal Louisiana and population decline.

Parish*es*	Mean change in population growth by 1 hectare of lost wetland (percentage points)	Mean loss of population per hectare of lost wetland
Cameron	−0.64	−6
Iberia	−4.14	−29
Jefferson	−3.88	−887
Lafourche	−1.14	−19
Orleans	−11.59	−9252
Plaquemines	−0.47	−24
St. Bernard	−2.87	−869
St. Charles	−5.7	−92
St. John the Baptist	−34.79	−582
St. Mary	−2.98	−32
St. Tammany	−8.54	−1377
Terrebonne	−0.44	−31
Vermilion	−2.32	−11
Mean value	**−6.12**	**−1016**

Source: [27].

On the other hand, some parishes like Cameron and Plaquemines show less drastic effects, with lower population losses per hectare. However, even these parishes experience negative effects, as seen in the −0.64% and −0.47% population growth per hectare for Cameron and Plaquemines, respectively. The mean values at the bottom of the table summarize the overall trend, showing an average population growth loss of −6.12 percentage points and a population loss of 1016 people per hectare of wetland lost. This table highlights the significant and widespread impact of wetland loss on population dynamics across coastal Louisiana. The population counterfactual analysis, which assesses how population levels would have evolved without wetland loss from 1990 to 2021, reveals the significant effect of wetland loss on population trends. The analysis compared the projected population, had wetlands not been lost, with the actual population, showing the difference as a percentage. For example, Cameron Parish experienced a notable population decline, while parishes like St. John the Baptist, St. Tammany, and Iberia saw modest population increases (1.37%, 1.53%, and 2.55%, respectively). In contrast, Cameron, Plaquemines, and St. Bernard parishes showed much higher differences, with increases of 62.72%, 154.32%, and 249.26%, respectively, emphasizing the long-term effects of wetland loss on population growth [27]. However, although loss of wetlands is closely linked to population decline by raising flood risks and environmental vulnerabilities, it is not the sole driver of changes in population. Social and economic factors such as job availability, urban development, housing, and migration trends also contribute to population declines.

3.2. Sea Level Rise in Louisiana

Figure 2 presents annual data on a measured variable over several decades, with notable variability from year to year. The early years show relatively low values, ranging from 0 to 3 inches, with some fluctuations. As the years progress, particularly from the 1970s onward, the measurements increase significantly, with many years surpassing 10 inches, and the figures peaking at around 24.07 inches in 2016. This trend suggests a gradual rise in the measured variable over time, with the most significant increases occurring after the 1980s. The data indicates that the variable being tracked has experienced considerable fluctuations, but the overall pattern seems to be one of rising intensity or volume over the decades. This could point to environmental or climate changes that may be influencing measurements.

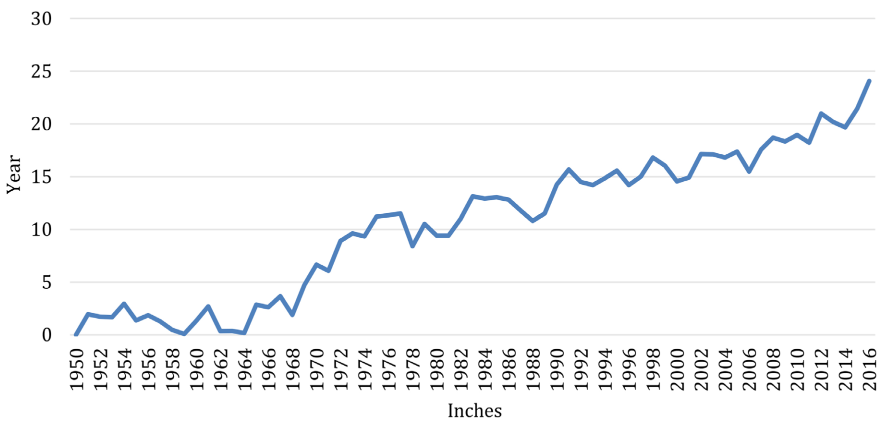

Figure 2. Sea level rise in Louisiana. Source: [29].

Louisiana is losing about 25 square miles of land each decade, putting its coastal marshes, which protect inland areas and provide wildlife habitat, in jeopardy. In response, Louisiana is investing over $25 billion in solutions to address sea level rise, including constructing levees, restoring shorelines, and relocating communities [29].

3.3. Degree of Flood Risk among Some Parishes in Louisiana

Many parishes in Louisiana face varying degrees of wetland loss and storm surge-related flood risk over the next 50 years, depending on environmental conditions and mitigation efforts. Acadia, Ascension, Assumption, Iberville, Lafayette, Livingston, St. Martin, and Tangipahoa parishes face minimal wetland loss and relatively low flood risk in Table 2. However, localized flooding may increase, particularly near rivers and low-lying areas. Calcasieu, Jefferson, St. Bernard, St. Charles, St. James, St. John the Baptist, St. Tammany, and Vermilion parishes are at greater risk, with rising flood depths (up to 16 feet or more in some areas). Wetland loss and storm surge threats are significant in exposed areas. Cameron, Iberia, Lafourche, Orleans, Plaquemines, and Terrebonne parishes face extensive wetland loss and extreme flooding risks. Flood depths could exceed 20 feet in some locations, particularly outside levee protection systems [11]. Without coastal protection or restoration actions, flood risk will increase significantly, particularly in southern and coastal regions.

Table 2. Degree of flood risk among some parishes in Louisiana.

Parish	100-year flood depths (feet)
Acadia	7 - 10
Ascension	8 - 9
Assumption	7 - 10
Calcasieu	13 or higher
Cameron	15 or higher
Iberia	16 or higher
Iberville	1 - 3
Jefferson	10 - 13
Lafayette	0
Lafourche	-
Livingston	10 - 13
Orleans	20
Plaquemines	-
St. Bernard	16 - 21
St. Charles	16 or higher
St. James	4 - 7
St. John the Baptist	13 or higher
St Martin	-
St. Tammy	7 - 15
Tangipahoa	13 - 16
Terrebonne	10 - 13
Vermillion	16 or higher

3.4. The Rate of Land Loss in Louisiana

In **Figure 3**, the rate of land loss observations, represented by black dots on the graph, were complemented by satellite imagery and computer model simulations to account for changes in the land area and any potential errors in measurement. Between 1932 and 2016 (**Figure 3**), the data show a persistent pattern of wetland decline, with the most dramatic reductions occurring prior to the 1970s, followed by a slower yet continuous rate of erosion. Ultimately, the report leveraged extensive statistical tools, including the 95% confidence intervals indicated by the dashed blue lines in the trend analysis, to estimate trends and validate the accuracy of the observations.

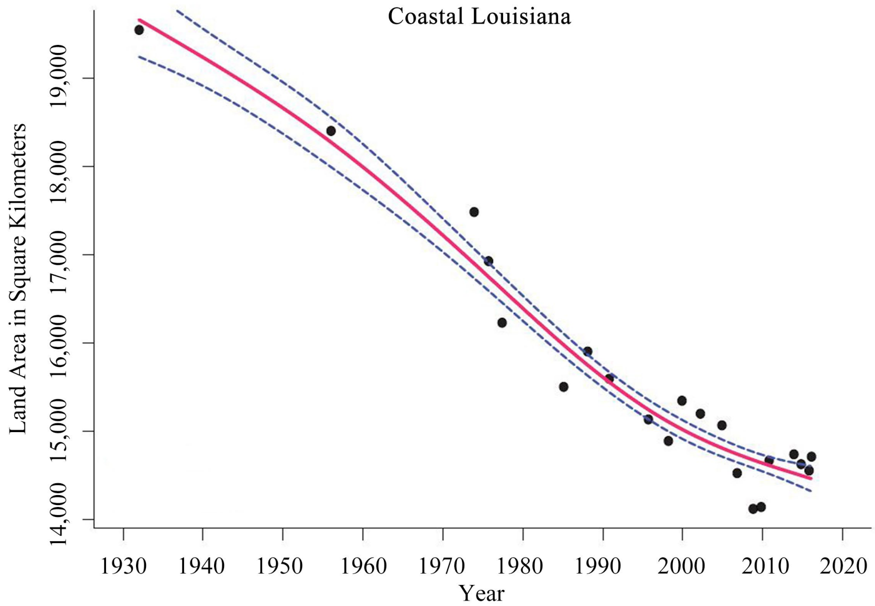

Figure 3. The rate of land loss in Louisiana. Source: [30].

The report estimates that Louisiana's coastal parishes have lost 5197 square kilometers (2006 square miles) of land from 1932 to 2016, with a margin of error of plus or minus 443 square kilometers (171 square miles). While the 2016 land area estimate, based on satellite data, showed a 16 square mile increase compared to 2010, a computer model accounting for potential errors revealed a decline of 151 square kilometers (58 square miles) since then. The difference between the 2010 and 2016 figures is within the margin of error, as coastal Louisiana's wetlands are constantly changing. Hurricanes Katrina and Rita caused the destruction of over 217 square miles of coastal wetlands, surpassing the wetland loss expected for the entire state over the next 20 years.

3.5. The Rate of Land Area Changes in Coastal Louisiana from 1932 to 2016

Figure 4 depicts the rate of land area change in coastal Louisiana from 1932 to 2016. The red line represents the estimated long-term land area change rate, while the dotted blue lines show the trend that would be produced in 95 out of 100 statistical analyses, indicating a consistent pattern [30]. The 2016 land area estimate for Louisiana, based on satellite data, was about 16 square miles higher than the 2010 estimate. However, after accounting for factors like changing water levels through a computer model, a statistical analysis revealed that the land area actually decreased by 151 square kilometers (58 square miles) since 2010. The difference between the two estimates is within the expected margin of error for measuring the dynamic wetlands. The study also found that land loss rates have been decreasing since the 1970s, though it is uncertain whether this trend will continue.

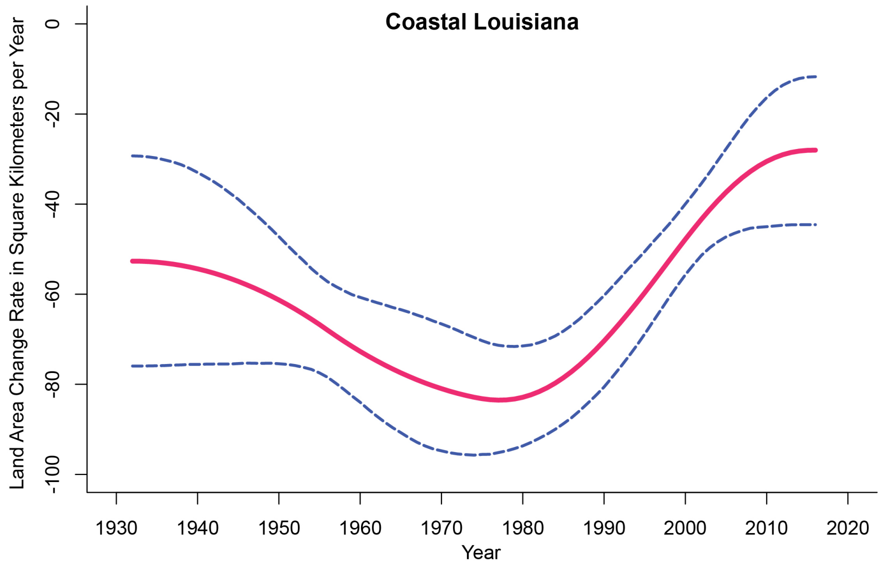

Figure 4. The rate of land area changes in coastal Louisiana from 1932 to 2016. Source: [30].

The Nelson Group's study also outlined the economic impacts of coastal erosion in Louisiana, including disruptions in the oil, gas, transportation, and commercial fishing industries. The Nelson Group also analyzed the continuous effects of coastline loss on commercial fishing, estimating significant long-term losses [28]. Researchers analyzed data from 21 observations between 1932 and 2016 (represented by black dots) in **Figure 4** and used statistical methods to determine the trend of wetland loss. The solid red line indicates that Louisiana's coastal wetlands experienced rapid decline until the 1970s, followed by a slower but continuing loss. Although some recent data points are higher than the red line, the earlier losses have a strong influence on the overall trend, which still shows a decline. The dashed blue lines represent a range where there is a 95% probability that the actual trend falls.

3.6. The Impact of a Three-Week Louisiana Oil Disruption on Sales, Earnings, and Employment

Table 3 illustrates the financial impact of disruptions in the oil, natural gas, maritime, and commercial fishing industries, highlighting losses in sales, earnings, and employment. A three-week oil disruption leads to $68.2 million in lost sales, $19.9 million in lost earnings, and 831 job losses, while extending it to five weeks raises the losses to $114.1 million in sales, $33.2 million in earnings, and 1389 jobs lost. Similarly, a three-week disruption in natural gas results in $57.4 million in lost sales, $12.9 million in earnings, and 491 lost jobs, showing a slightly lower impact than oil disruptions.

Table 3. The impact of a three-week Louisiana oil disruption on sales, earnings, and employment.

Impact	Lost Sales (Millions)	Lost Earnings (Millions)	Lost Employment
Three-Week Oil Disruption	$68.2	$19.9	831
Five-Week Oil Disruption	$114.1	$33.2	1389
Three-Week Natural Gas Disruption	$57.4	$12.9	491
Seven-Day Closure of the Lower Mississippi	$11.5	$3.1	120
Fourteen-Day Closure of the Lower Mississippi	$46.1	$12.4	480
Annual Impact of Additional Barge Costs	$3.5	$0.5	20
Commercial fishing	$4192.6	$1017.9	N/A
Aggregation of Economic Impact (Short-Term)	$860.9	$268.7	13,459
Aggregation of Economic Impact (long term)	$941.4	$291.3	14,377

Source: [28].

A seven-day closure of the Lower Mississippi causes $11.5 million in lost sales, $3.1 million in earnings, and 120 job losses, while a fourteen-day closure significantly increases the impact to $46.1 million in lost sales, $12.4 million in earnings, and 480 jobs lost. This demonstrates the river's crucial role in economic activities such as transportation and logistics. Increased annual barge transportation costs lead to $3.5 million in lost sales, $0.5 million in earnings, and 20 lost jobs, making this impact relatively minor compared to other disruptions. The commercial fishing industry experiences the most significant financial losses, with $4.19 billion in lost sales and $1.02 billion in lost earnings. Though employment figures are unavailable, the scale of financial loss suggests thousands of jobs are affected, making commercial fishing highly vulnerable to economic and environmental disruptions. The combined short-term economic impact across multiple disruptions results in $860.9 million in lost sales, $268.7 million in lost earnings, and 13,459 jobs lost. Over the long term, the impact rises to $941.4 million in lost sales, $291.3 million in lost earnings, and 14,377 jobs lost, indicating that financial repercussions extend beyond the immediate effects of these disruptions.

3.7. The Present Value of Economic Losses Resulting from Frequent Disruptions in Louisiana from Now until 2050 (Short-Term to Long-Term Impacts)

Table 4 shows the potential economic impact of recurring disruptions, showing a direct correlation between the frequency of disruptions and financial losses. When disruptions occur every six years, lost sales range from $26.0 to $38.7 billion, with lost earnings between $7.1 and $18.6 billion. Increasing the frequency to every four years results in significantly higher losses, with sales declining by $49.8 to $74.0 billion and earnings dropping by $13.5 to $20.4 billion. If disruptions become an annual occurrence, the economic consequences are far more severe, with lost sales soaring to between $145.0 and $215.7 billion, while lost earnings range from $39.5 to $59.3 billion. The absence of employment data suggests that job losses could be substantial but are not explicitly quantified. These figures highlight the escalating financial burden of frequent disruptions and the need for long-term mitigation strategies to prevent widespread economic instability.

Table 4. The present value of economic losses resulting from frequent disruptions in Louisiana from now until 2050 (Short-term to long-term impacts).

Disruption Rate	Lost Sales (Billions)	Lost Earnings (Billions)	Lost Employment
Disruptions occurring every six years	$26.0 to $38.7	$7.1 to $18.6	-
Disruptions occurring every four years	$49.8 to $74.0	$13.5 to $20.4	-
Disruptions occur every year	$145.0 to $215.7	$39.5 to $59.3	-

Source: [28].

The economic consequences of energy disruptions, transportation issues, and environmental challenges indicate that the oil and gas sectors, Mississippi River trade, and commercial fishing are especially at risk. To minimize these effects, policymakers and industry leaders should prioritize strengthening infrastructure, reducing reliance on single industries, and enhancing emergency response strategies.

3.8. Projected Losses for Louisiana's Fishing-Related Businesses Caused by the 2020-2021 Hurricanes

The 2020-2021 hurricanes had a significant economic impact on Louisiana's fishing-related businesses. In 2020, estimated losses ranged from about $117 million to $205 million, with an average of approximately $161 million in Table 5. Losses increased in 2021, falling between $329 million and $427 million, with an average of $378 million. By 2022, the financial effects persisted but at a smaller scale, with losses estimated between $15 million and $67 million, averaging around $41 million. Overall, the total estimated losses over these three years range from $461 million to $699 million, with an average of roughly $580 million. These figures illustrate the high and ongoing vulnerability of Louisiana's fishing sector to severe weather events, emphasizing the importance of targeted mitigation, restoration, and economic support strategies.

Table 5. Projected losses for Louisiana's fishing related businesses caused by the 2020-2021 hurricanes.

Impacts	Lower bound	Upper bound	Average
2020	$117,234,920	$204,877,431	$161,056,176
2021	$329,029,692	$427,267,497	$378,148,594
2022	$14,843,302	$66,589,135	$40,716,219
Total Impacts	$461,107,914	$698,734,064	$579,920,989

Source: [31].

4. Discussion

4.1. Land Loss Analysis in Coastal Louisiana

Louisiana holds 25 percent of the vegetated wetlands and 40 percent of the coastal and estuarine wetlands in the contiguous United States. The findings highlight the intricate connections among environmental decline, population dynamics, and economic instability across coastal Louisiana. Collectively, these interrelated factors generate overlapping risks that intensify one another, driving continued land loss, destabilizing communities, and endangering the state's economic resilience. As wetlands disappear, their ability to buffer storms and absorb floodwater weakens, leaving nearby communities and livelihoods increasingly vulnerable. These environments, including bays and estuaries, support renewable natural resources valued at over $1 billion annually. The state unfortunately experiences the highest rate of wetland loss, accounting for 80 percent of the total wetland loss nationwide [17]. Since 1956, Louisiana has lost over 2500 square kilometers of coastal wetlands due to erosion and conversion into open-water habitats, according to measurements by the U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service.

[19] also suggests that wetland loss is driven by both natural processes, like sea-level rise, and human development. Coastal wetlands are vital as nursery areas for marine species, contributing significantly to marine productivity. They also act as buffers, reducing the impact of major storms onshore. Coastal wetlands offer vital ecosystem services such as habitat for diverse species, nutrient cycling, carbon storage, recreational resources, and protection from flooding and storm surges. Unfortunately, these wetlands face significant threats from sea level rise, subsidence, erosion, reduced river sediment supply, hurricanes, human development, and peat collapse [9]. [19] further points out that Louisiana's Mississippi River delta and chenier plains are also losing over 100 km^2 of land each year, representing a severe decline in coastal wetlands. This will have a significant negative effect on industries such as fisheries, fur, and waterfowl, which rely on the habitat these

estuaries provide. These industries are valued at approximately $1 billion annually [19].

Additionally, wetland loss is driven by spoil disposal on wetlands and land reclamation projects [32]. Some wetlands are transformed into spoil banks and other ecosystems, suggesting that actual wetland losses may be two to three times higher. In the Barataria Bay basin, annual wetland losses account for 2.6% of the total wetland area. The relationship among hydrology, land, vegetation, substrate, subsidence, and sediment supply is complex, but areas with high canal density generally see higher land loss rates, which may be accelerating [32]. [16] also highlights that the decline and loss of wetlands in the Mississippi River delta plain are mainly caused by human intervention rather than natural processes. Levees have prevented seasonal flooding, which once supplied crucial sediment to the wetlands. Also, dredged canals and flood-control measures have facilitated the intrusion of saltwater into freshwater wetlands.

Globally, [33] attests that Louisiana experiences some of the highest rates of coastal retreat and land loss. Particularly, Southern Louisiana is affected by land subsidence caused by frequent flooding from hurricanes and tropical storms [12]. This situation is severe due to the added human infrastructure on Louisiana's delta. Since the 1930s, Louisiana has lost nearly 1.2 million acres (1875 square miles) of coastal land. This rapid land loss poses a significant threat to key national resources and local communities that depend on them [20]. Pipelines, navigation channels, fisheries, along with centuries-old human settlements and invaluable ecosystems, are all at risk in coastal Louisiana.

Given the economic, cultural, and historical significance of the region to the United States, the loss of these diverse and essential environments represents a looming national disaster. This is as a result of factors such as sediment compaction and subsidence, and reduced sediment supply caused by dams and levees. The compaction of sediments, combined with sea-level rise, results in a relative rise in sea level that is nearly three times higher than the global average. It is essential to determine the timing and extent of these changes to allow adequate preparation and mitigation efforts [19]. The opposing view argues that human activities play the dominant role, with natural processes being of lesser significance [19]. While natural processes have contributed to this loss, human activities like dredging wetlands for canals or draining and filling land for agriculture, grazing, or development have played a significant role in altering and destroying marsh habitats.

4.2. Louisiana's Population Dynamics and Coastal Land Loss

Overall, the data shows that as wetlands disappear, populations fall, with the sharpest declines occurring in Orleans, Jefferson, and St. Tammany parishes. These combined effects of land loss and population decline intensify Louisiana's economic vulnerabilities. For instance, New Orleans, located at the coast of Louisiana, is one of the cities prone to water-related natural disasters such as hurricanes, flooding and storms which are considered to play a significant role in the parish's recent population dynamics [34]. This growing vulnerability cannot be considered in isolation: wetland degradation heightens flood exposure, which drives population outmigration, ultimately shrinking the tax base essential for funding future protection and restoration efforts. Population growth in parishes like St. John the Baptist and St. Tammany reflects broader inland migration, where urbanization and demographic shifts are placing additional demands on infrastructure, housing, and public services. While much of the shoreline is retreating and coastal bays are expanding at the expense of wetlands, the Wax Lake and Atchafalaya deltas are advancing and creating new delta plains. Coastal processes shaping the lower delta plain and coast are relatively mild, with low wave energy and a microtidal regime. However, occasional hurricanes and more frequent frontal systems can raise water levels and generate large waves (over 1 to 2 meters), leading to erosion, over-wash, and breaches in the barrier islands [35].

Combining fluctuating precipitation patterns and increasingly frequent hurricanes, the hydrologic balance of southern Louisiana faces mounting stress [36] [37]. In light of these interrelated challenges, mitigation strategies must be evaluated not only for their short-term effectiveness but also for their long-term sustainability, economic costs, and ecological implications. Louisiana's Coastal Master Plan, which allocates over $25 billion in investments, emphasizes an integrated approach that combines restoration and protection initiatives such as river sediment diversions, barrier island reconstruction, and levee enhancement. Even though wetland loss influences these dynamics by raising flood risks and environmental vulnerabilities, overall population changes also result from a combination of ecological and socioeconomic factors. That is, despite the clear connection between wetland loss and population decline, other social and economic factors such as job availability, urban development, housing, and migration patterns also play significant roles in shaping population trends. However, counterfactual analyses suggest that, without wetland degradation, these coastal areas could have retained thousands more residents between 1990 and 2021.

4.3. Economic Implications from Coastal Erosion

The 2004 study by Richardson and Scott projected the present value of economic losses from recurring disruptions in the state's economy through 2050. The 2004 study also addressed broader economic disruptions across multiple sectors, whereas the 2020-2022 data provided concrete examples of losses to a critical industry. It is estimated that disruptions occurring every six years could result in lost sales between $26.0 and $38.7 billion and lost earnings between $7.1 and $18.6 billion. More frequent disruptions every four years were projected to cause $49.8 to $74.0 billion in lost sales and $13.5 to $20.4 billion in lost earnings, while annual disruptions could lead to $145.0 to $215.7 billion in lost sales and $39.5 to $59.3 billion in lost earnings. These projections highlighted the increasing financial risks associated with more frequent economic disruptions. In contrast, the 2020-2021 hurricanes had a substantial but more localized impact, specifically affecting Louisiana's fishing-related businesses. Estimated losses over this period totaled approximately $579 million, including damages to infrastructure, lost revenue, and depletion of resources.

Although these actual losses are far smaller than the statewide projections from 2004, the figures reflect tangible, sector-specific impacts that the earlier projections could not capture. The state's coastal region underpins major industries such as oil and gas, shipping, and commercial fishing that contribute billions of dollars to the economy each year. Yet, persistent wetland degradation and recurrent flooding are disrupting these critical sectors, with projected cumulative losses ranging from $7 billion to $59 billion by 2050. While projected losses offer a useful framework for understanding potential risks under different disruption scenarios, actual events provide essential context for validating and updating these projections. The severity of losses depends on the scope and frequency of disruptions, emphasizing that more frequent or widespread events could generate losses approaching the high-end projections. Finally, integrating both projected and observed data allows for a more comprehensive understanding of economic vulnerability, guiding both long-term planning and immediate mitigation strategies for Louisiana's coastal industries.

4.4. Restoration Efforts and Mitigation Strategies

Considering the pressing nature of the issue, a variety of measures aimed at mitigating and adapting to the challenges of coastal erosion and sea level rise in Louisiana have been put into action and suggested. These strategies encompass a spectrum of approaches, ranging from engineered solutions, such as the construction of levees and floodgates, to natural solutions, including the restoration of marshes and the creation of barrier islands [4]. Successful restoration will involve using sediment and freshwater strategically, such as for barrier island restoration, marsh creation, and diversions to restore natural processes. A balanced approach is needed to address both ecological factors and subsurface geology [20]. To effectively evaluate coastal protection methods, it is crucial to understand the natural and human-induced processes driving barrier island erosion, estuary degradation, and salt marsh loss in the Mississippi River delta plain. Past efforts in coastal preservation have shown that supporting natural processes is more effective than attempting to counter them. Like highways that require regular maintenance, coastal zones should have an ongoing program for beach nourishment, barrier restoration, shoreface nourishment, vegetation, and other coastal modification projects [19].

Barrier island restoration aims to counteract landward retreat and prevent island disintegration by adding sediment and modifying the environment. This process includes "soft options," such as dredged sediment placement to restore beaches, dunes, and marshes, along with stabilization techniques like sand fences and vegetation growth [38]. Similarly, marsh creation and nourishment involve mobilization, surveying, sediment dredging, and vegetation installation, with success depending on substrate characteristics and hydrologic exchange [20] [39]. Shoreline protection in coastal Louisiana often employs rock dikes and terraces, which trap sediment, reduce wave impact, and enhance habitat conditions by promoting vegetation growth [20]. Also, river diversions reconnect the Mississippi River to its delta, delivering freshwater, nutrients, and sediments to sustain coastal wetlands, mitigate salinity stress, and combat nutrient overload contributing to the Gulf of Mexico's dead zone [20].

Since coastal wetland changes are a long-term process, influenced by factors such as rivers, tides, and storms, it is recommended that near-term strategies continue using dedicated dredging and beneficial reuse of dredged materials to create new wetlands and barrier islands. At the same time, efforts are being made to improve sediment management, aiming to better inventory and utilize available sediment, both renewable and nonrenewable. This includes exploring ways to use the millions of cubic yards of sediment dredged annually from navigational channels, rather than disposing of it [20]. Programs like SWAMP monitor wetlands, barrier islands, sediment resources, and water quality, collaborating with state and federal agencies. Efficient management of resources, especially sediment, is crucial. The Office of Coastal Protection and Restoration is working on more comprehensive monitoring and sediment management plans to support a holistic coastal management approach. This monitoring has provided valuable data to understand the effects of repeated coastal impacts (e.g., hurricanes, oil spills) and offers a foundation for viewing the coast as a system [20].

Proposals to address the loss of barrier islands and wetlands in Louisiana include soft engineering solutions like renourishing barrier islands with dredged materials and creating new navigation channels to allow natural erosion. These strategies could impact local communities, agriculture, and the oil industry. Hard engineering options, such as sea walls and breakwaters, are also considered, but they are costly and have had mixed results [16]. To formulate a comprehensive coastal management plan, it is essential to conduct a thorough assessment of the effectiveness and feasibility of these measures. Therefore, the future of coastal Louisiana depends on understanding its geological and ecological structure, the impacts of landscape changes, and the trade-offs of management actions.

5. Conclusions

Researchers have long acknowledged the severe coastal land loss in Louisiana, but its causes remain debated. Over the past decade, two main perspectives have emerged among coastal scientists. One view prioritizes natural delta cycle processes as the primary driver, considering human activities as a secondary factor. For instance, sea level rise is threatening coastal regions, making them more vulnerable to flooding and shoreline retreat. This loss is most pronounced in younger deltas near the coast and lower in older, more consolidated areas. Canal density strongly influences land loss rates, with an average loss of 0.09% annually at zero canal density. Sea-level rise, regardless of its scale, will raise salinity levels in rivers, bays, and estuaries, worsen saltwater intrusion into aquifers, flood productive coastal vegetation, and significantly increase coastal erosion and land loss. River diversions are designed to reconnect the Mississippi River with its delta wetlands, delivering sediment that helps naturally rebuild and sustain land. Although this approach supports long-term ecological recovery, it is expensive and can be politically sensitive due to its effects on local fisheries and communities. Barrier island restoration projects, like those in the Barataria and Terrebonne basins, offer essential protection against storms and support valuable habitats. However, these islands require ongoing maintenance, as they tend to erode within decades if sediment replenishment is not continuously provided. Levee systems and floodwalls, crucial for protecting urban areas from storm surges, offer immediate defense but can unintentionally accelerate land subsidence by blocking natural sediment deposition. Their substantial upkeep costs also raise concerns about their long-term economic viability.

In summary, the challenges of sea level rise and coastal erosion in Louisiana require urgent and continuous action. This research underscores the significant effects these environmental issues have on the state's economy, infrastructure, and communities. Through comprehensive and coordinated mitigation efforts such as enhancing coastal restoration, improving infrastructure, and enacting forward-thinking policies, Louisiana can strengthen its resilience to these persistent threats. By integrating ecological restoration, cutting-edge engineering methods, and climate action plans, the state can protect its critical ecosystems and industries, ensuring its long-term sustainability. Moving forward, cooperation among policymakers, scientists, and local communities will be crucial to help Louisiana adapt to these challenges and preserve its invaluable coastal resources for future generations. Although each mitigation strategy targets a particular aspect of the coastal crisis, its success relies on integrated and adaptive management that accounts for both ecological and social factors. For instance, pairing sediment diversions with carefully planned barrier island restoration can produce synergistic effects, strengthen natural defenses and lessen dependence on engineered infrastructure. Likewise, managed retreat and community relocation initiatives should be accompanied by economic transition planning to help displaced residents sustain their livelihoods. Overall, the findings have shown that Louisiana's coastal challenges form a multi-faceted, self-reinforcing system, in which environmental degradation, population changes, and economic losses interact to amplify risks. Effectively addressing these issues requires not only technical solutions but also enduring policy support, active community involvement, and coordination across sectors. The state's long-term resilience will hinge on its ability to integrate ecological restoration with social and economic adaptation strategies.

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Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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