The Sundarbans Under Threat: Climate Change Impacts on Biodiversity, Habitats, and Human Livelihoods

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ABSTRACT

The Sundarbans mangrove ecosystem, located in the delta formed by the Ganges, Brahmaputra, and Meghna rivers, plays a crucial role in global biodiversity and climate regulation. This analysis focuses on the impact of climate change on this unique environment, examining factors such as rising sea levels, increasing temperatures, changing precipitation patterns, and more frequent severe cyclones. Rising sea levels and higher salinity are reshaping the mangrove species composition, affecting their growth and reproductive processes. Temperature increases exacerbate these changes, disrupting the ecosystem's delicate balance and altering species distributions and interactions. Shifts in precipitation patterns reduce freshwater inflows, worsening salinity intrusion and affecting both plant and animal life. More frequent and intense cyclones are accelerating erosion and habitat loss, affecting not only the mangroves but also the human populations that rely on this ecosystem for fishing and agriculture.The socio-economic consequences are significant, as climate-driven changes threaten the livelihoods of local communities. This review explores adaptive management strategies, including community-led conservation and policy initiatives, as essential tools for mitigating these impacts and building resilience. It calls for integrated, interdisciplinary approaches to safeguarding the Sundarbans, urging enhanced international cooperation, sustainable management practices, and focused research to confront climate change challenges and protect this critical ecological and socio-economic resource

.**Keywords:** *Mangrove Ecosystem, Sea Level Rise, Salinity Intrusion, Precipitation Patterns, Cyclone Intensity, Biodiversity.*

I. INTRODUCTION

The Sundarbans, the world's largest contiguous mangrove forest, straddles the delta of the Ganges, Brahmaputra, and Meghna rivers in Bangladesh and India. It provides a wide array of ecosystem services and contributes significantly to the socio-economic development of the region (Rahman, 2009; SCBD, 2009). Around 3.5 million people living near the Sundarbans rely directly or indirectly on the environmental services it offers, such as fisheries, timber, and non-timber forest products (Giri et al., 2007; Biswas et al., 2007). Covering about 140,000 hectares, the Sundarbans is a dynamic ecosystem of tidal canals, mudflats, and salt-tolerant mangrove islands. Its biodiversity includes 260 bird species, Bengal tigers, and endangered animals like the Indian python and estuarine crocodile (whc.unesco.org).

As a UNESCO World Heritage site, the Sundarbans not only protects coastal areas from storm surges but also sustains a rich variety of terrestrial, aquatic, and marine life. It is home to internationally threatened species, including the unique river terrapin, the Ganges and Irawadi dolphins, and the Royal Bengal Tiger—the only tiger species adapted to mangrove habitats. These diverse ecosystems, however, face significant risks due to climate change.

Rising sea levels, increasing temperatures, and altered precipitation patterns are severely affecting the Sundarbans. Salinity intrusion caused by sea-level rise is disrupting the growth of mangrove species and changing the region's ecological balance. Meanwhile, freshwater scarcity and higher temperatures further stress the mangrove environment. More frequent and intense cyclones are eroding the coastline, leading to habitat loss and increased vulnerability to storm surges.

This analysis delves into how climate change is compounding the environmental and socio-economic challenges in the Sundarbans. By reviewing current research, the study highlights the intricate interplay of environmental changes and their consequences for both the ecosystem and local livelihoods. It also examines adaptive management strategies, such as community-based conservation efforts, to mitigate these impacts. Protecting the Sundarbans is essential to safeguarding its ecological functions and the well-being of the millions who rely on it for survival in an era of increasing climate uncertainty.

II. OBJECTIVES

- To evaluate how climate change-induced factors such as rising sea levels, increasing temperatures, altered precipitation patterns, and intensified cyclones are affecting the Sundarbans mangrove ecosystem.
- To analyze the shifts in species composition, distribution, and interactions within the mangrove ecosystem as a result of climate change.
- To review and evaluate current and proposed adaptive management strategies aimed at mitigating the adverse effects of climate change on the Sundarbans, including community-based conservation efforts and policy interventions.

III. METHODOLOGY

This research employs a multi-disciplinary approach to comprehensively analyze the impacts of climate change on the Sundarbans mangrove ecosystem. The methodology is structured to integrate qualitative and quantitative data collection and analysis methods, ensuring a holistic understanding of the various dimensions of climate change effects on this unique ecosystem.

Climate change-induced factors such as rising sea levels, increasing temperatures, altered precipitation patterns, and intensified cyclones are affecting the Sundarbans mangrove ecosystem

Climate change is having profound and multifaceted impacts on the Sundarbans mangrove ecosystem, driven by factors such as rising sea levels, increasing temperatures, altered precipitation patterns, and intensified cyclones. Each of these factors interacts with the others, creating a complex web of challenges that threaten the ecological balance of the Sundarbans and the livelihoods of the communities that depend on it.

- **Rising Sea Levels**

When the yearly sea level variation is compared, it can be seen that between 1985 and 1998, the annual mean sea level increased steadily. This suggests a minimal increase in relative sea level of 4 cm over a 14-year period. The net rate of sea level rise in the Ganga-Brahmaputra delta would be 3.14 mm year, accounting for the high sedimentation burden of 0.1 mm year. This is a substantial increase over the current trend of an average annual rise in sea level of 2 mm worldwide. By 2050, the compounded sea level elevation is predicted to approach one meter, based on the current relative sea level rise of 3.14 mm annually (Hazra et al., 2002).

- **Impact on Mangrove Habitat:**

Rising sea levels, driven by the thermal expansion of seawater and the melting of polar ice caps, are leading to the gradual submersion of the Sundarbans' low-lying areas. This results in the loss of mangrove habitat, as these forests are squeezed between encroaching saltwater and the landward movement of tidal creeks. Mangrove species that are

less tolerant of prolonged submersion or increased salinity are particularly vulnerable, leading to shifts in species composition.

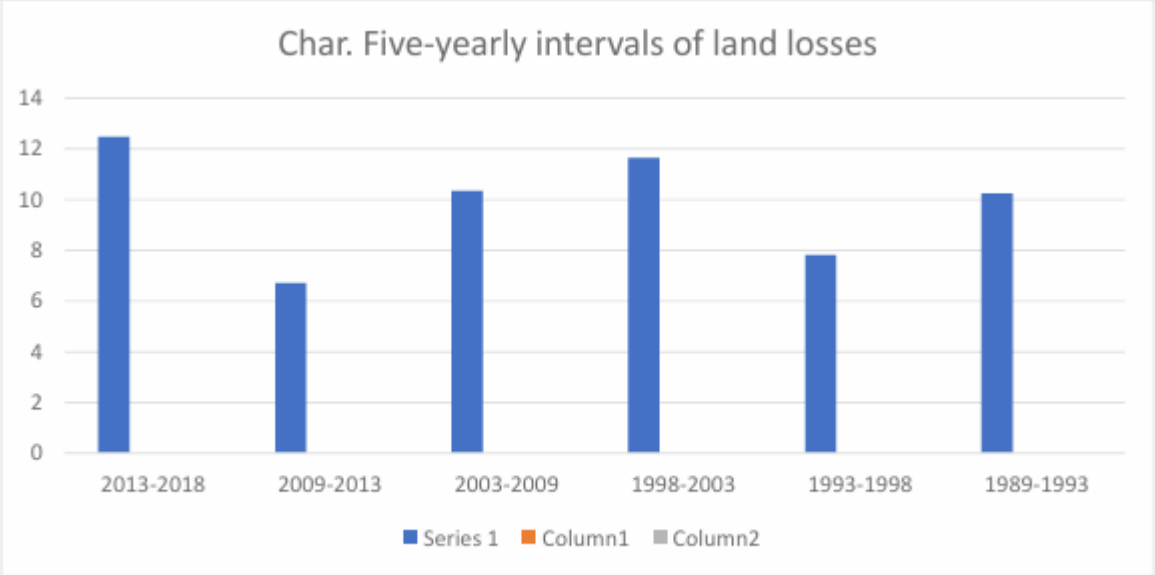
In every instance, there has been a notable decrease in mangroves; the losses increase with sea level rise. If current management continues, the mangroves of the Indian Sundarbans could lose between 42% and 80% of their current area by the end of the century (Samanta et al., 2023).

https://www.sciencedirect.com/science/article/abs/pii/S004896972305249X

Table 1. Five-yearly intervals of land losses the entire coastline of the Sundarbans.

Land losses (km2)	Intervals
12.48	2013-2018
6.70	2009-2013
10.35	2003-2009
11.65	1998-2003
7.82	1993-1998
10.25	1989-1993

Source: https://www.sciencedirect.com/science/article/pii/S1018363921001136#t0025



Char 1. Five-yearly intervals of land losses the entire coastline of the Sundarbans

- **Increased Salinity:**

As sea levels rise, saltwater intrudes further into the estuarine system, increasing the salinity of both soil and water. This heightened salinity stresses the mangrove trees, especially those adapted to lower salinity levels, reducing their growth, reproductive success, and survival. Species such as Avicennia and Excoecarianin, which are more salt-tolerant, may begin to dominate, altering the overall biodiversity of the ecosystem. Only in the western sector were distinct tidal fluctuations in salinity recorded; in other regions, the salinity difference between low and high tides was minimal, ranging from 1.4 to 2.0 ppt. In contrast, the entire ecosystem saw very noticeable seasonal fluctuations in salinity, ranging from 9.34 to 30.83 ppt. Most of the Sundarbans utilized to experience saline levels that were roughly comparable during the summer (29.0–30.0 ppt) and monsoon (12.0 14.0 ppt), showing less degrees of spatial fluctuation. However, winter and pre-summer saw substantial saltwater variations upstream and downstream,

with comparatively greater levels in most estuarine networks, indicating more fresh water inflow in this area. (Sarkar et al., 2013)

https://www.researchgate.net/profile/Phanibhusan-Ghosh/publication/330968343

- **Increasing Temperatures**

By 2081–2100, global temperatures are expected to rise by up to 4.8°C from 1986–2005 (IPCC,2013, RCP8.5).

- **Effects on Species Distribution:**

Rising temperatures directly affect the physiological processes of mangrove species, influencing growth rates, phenology, and geographic distribution. Warmer temperatures can lead to shifts in the distribution of species, with some species moving poleward or to higher elevations in search of suitable conditions. This may disrupt existing ecological relationships and lead to the decline of species that are unable to adapt quickly enough. Mangrove species diversity, phenology, productivity, or eventually the latitudinal geographic region of their distribution are expected to be impacted by this temperature increase. Many mangroves are currently latitudinally limited by the lowest air temperature of 16° C during the coldest month (Saenger 2002). at 28 32°C, when leaf photosynthesis peaks (Ball and Sobrado 2002). in addition to low sea temperatures, which might shorten propagules' floating time (Duke et al. 1998) Although short-term freezes events have a higher impact on latitudinal distribution in certain places, most notably North America (Cook-Patton et al. 2015).

- **Impact on Ecosystem Functioning:**

Increased temperatures can also exacerbate other stressors, such as drought conditions and altered water availability. Higher temperatures may increase the rate of evapotranspiration, leading to drier conditions that further stress the mangroves. Additionally, the reproductive cycles of many species, including the iconic Bengal tiger, may be disrupted, leading to reduced population sizes and altered predator-prey dynamics.

- **Altered Precipitation Patterns**

➢ **Changes in Freshwater Availability:**

Climate change is causing shifts in precipitation patterns, with some areas experiencing more intense rainfall and others facing prolonged droughts. For the Sundarbans, changes in precipitation directly affect the inflow of freshwater from the Ganges, Brahmaputra, and Meghna rivers. Reduced freshwater inflow increases salinity levels in the estuarine system, further stressing the mangrove ecosystem. Conversely, excessive rainfall can lead to flooding, which can erode shorelines and wash away young mangrove saplings. ¬ Impacts on Ecosystem Services: Altered precipitation patterns also impact the ecosystem services provided by the Sundarbans, such as water purification, carbon sequestration, and habitat provision. Changes in freshwater flow can disrupt nutrient cycling, reduce the availability of fresh water for local communities, and diminish the mangroves' ability to sequester carbon, exacerbating global climate change.

- **Intensified Cyclones**

➢ **Physical Damage to Mangroves:**

The Sundarbans is frequently struck by cyclones, which are becoming more intense due to climate change. These storms cause extensive physical damage to the mangroves, uprooting trees, eroding shorelines, and destroying habitats. The increased frequency and intensity of cyclones mean that the mangroves have less time to recover between events, leading to a gradual decline in forest health and resilience. A TC can cause indirect harm to mangroves by causing hydrological or environmental changes including ponding and hyper salinization, as well as direct harm from physical forces like wind and storm surges. Such damage typically shows up as tree death, reduced canopy cover, and defoliation at the community level (Hogan et al. 2020; Krauss and Osland 2020). Numerous elements, such as the storm's characteristics (wind speed, total rainfall, etc.) and the site's proximity to the storm track (distance and track quadrant) affect the extent of damage at a given place (Svejkovsky et al.2020; Taillie et al.

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➢ Impact on Biodiversity and Livelihoods:

Cyclones also have a devastating impact on the biodiversity of the Sundarbans. Species that depend on specific habitats, such as the Bengal tiger, may find their territories and prey populations diminished. Furthermore, the human communities living in and around the Sundarbans are severely affected by cyclones, with homes, infrastructure, and livelihoods being destroyed. The loss of mangroves, which act as a natural barrier against storm surges, exacerbates the vulnerability of these communities.

The interplay of rising sea levels, increasing temperatures, altered precipitation patterns, and intensified cyclones is profoundly altering the Sundarbans mangrove ecosystem. These climate change-induced factors are not only reshaping the physical landscape but also impacting the biodiversity, ecosystem services, and human communities that rely on the Sundarbans. The cumulative effect of these changes threatens the long-term sustainability of this critical ecosystem, underscoring the urgent need for effective conservation strategies, adaptive management, and international cooperation to mitigate the impacts of climate change on the Sundarbans.

Analyze the shifts in species composition, distribution, and interactions within the mangrove ecosystem as a result of climate change

Climate change is driving significant shifts in species composition, distribution, and interactions within the Sundarbans mangrove ecosystem. These changes are primarily influenced by factors such as rising sea levels, increasing temperatures, altered precipitation patterns, and more frequent and severe cyclones. The following analysis delves into how these factors are reshaping the ecological dynamics of the Sundarbans.

- **Shifts in Species Composition**

➢ Mangrove Species:

The rising salinity levels caused by sea-level rise and reduced freshwater inflow are altering the species composition within the Sundarbans. Mangrove species that are less tolerant to high salinity, such as Heritiera fomes (Sundri) and Nypa fruticans (Nipa palm), are experiencing declines in population. Conversely, salt tolerant species like Avicennia marina and Excoecaria agallocha are becoming more dominant. This shift in species composition can reduce the overall biodiversity of the mangrove forest, as the ecosystem becomes dominated by fewer, more resilient species. The mangrove islands of this ecoregion are home to various other threatened mammals, such as flying foxes, pangolins, fishing cats, and jungle cats, in addition to the tiger and its prey species. The fishing cat, as its name suggests, is a medium-sized wild cat with markings resembling those of a leopard that enters the water to capture fish and crabs at the channel's borders. There are also big, dangerous predators in the canals (oneearth.org). https://www.oneearth.org/ecoregions/sundarbans mangroves/

The waterways and the coastlines are home to two types of crocodiles: the salt-water crocodile and the mugger crocodile. The second largest lizard in the world, the water monitor lizard may reach a length of nine feet and hunts on land as well as in the water. The waterways are patrolled by Gangetic dolphins and sharks. The mudskipper, an air-breathing fish that emerges from the water into mudflats and even climbs trees, is less noticeable but no less fascinating. The mangrove woodlands are home to over 170 bird species, including 12 coexisting kinds of prey(oneearth.org). https://www.oneearth.org/ecoregions/sundarbans-mangroves/

Anthropogenic hazards are significant since this ecoregion spans two nations that have some of the greatest densities of people on Earth. For fuelwood, around half of the mangroves have been cleared. For the shrimp grow-out sector, shrimp fry is being harvested at unsustainable rates, and forests are being removed to make room for grow-out ponds. Projects involving diverting the river and impound upriver are having an impact on the delicate salinity and tidal flux balance that sustain this ecosystem. A few of the more serious dangers come from several thousand

kilometres away: the rivers that supply and cleanse the mangroves bring in large amounts of sediment from the Himalayan Mountain slopes that have been cleared of trees. The delicate mangrove ecosystems are severely impacted by this silt-filled, murky water, which also suffocates fish and shellfish eggs and young that use the mangroves as nurseries(oneearth.org).

➢ Faunal Species:

The changing environmental conditions are also impacting faunal species composition. Species that depend on specific habitat conditions, such as the Bengal tiger, spotted deer, and various fish species, are facing habitat loss and changes in prey availability. The decline in certain mangrove species can lead to reduced food resources and shelter, further stressing these animal populations. ϖ Changes in Species Distribution

➢ Mangrove Migration:

As sea levels rise and salinity increases, some mangrove species are migrating landward in search of less saline environments. This migration is constrained by the availability of suitable habitat and human development, which limits the space for mangroves to expand. Additionally, temperature increases may push some species toward the cooler, more temperate regions of the Sundarbans, altering the traditional zonation patterns of the mangrove forest.

➢ Faunal Range Shifts:

Animal species within the Sundarbans are also shifting their ranges in response to changing conditions. For instance, aquatic species may move further upstream to escape rising salinity levels, while terrestrial species may shift to less disturbed areas in response to habitat loss from cyclones or human encroachment. These shifts can disrupt established predator-prey relationships and lead to increased competition for resources in newly colonized areas.

- **Alterations in Species Interactions**

➢ Predator-Prey Dynamics:

The shifts in species composition and distribution have a cascading effect on predator-prey dynamics within the Sundarbans. For example, the decline in herbivorous species like the spotted deer due to habitat loss and increased salinity may reduce the prey base for predators such as the Bengal tiger. This can lead to increased tiger-human conflicts as tigers are forced to venture closer to human settlements in search of food.

➢ Competition and Symbiosis:

As species shift their ranges and new species compositions emerge, competition for resources intensifies. Mangrove species that are better adapted to the changing conditions may outcompete less resilient species, leading to shifts in dominance. Additionally, symbiotic relationships, such as those between certain mangrove species and their associated fauna (e.g., crabs, oysters), may be disrupted as environmental conditions change, leading to declines in the populations of both symbiotic partners.

- **Impact on Ecosystem Services**

➢ Biodiversity and Resilience:

The shifts in species composition, distribution, and interactions are leading to a reduction in biodiversity, which in turn affects the resilience of the Sundarbans ecosystem. A less diverse mangrove forest is more vulnerable to further environmental stressors, such as disease outbreaks or invasive species, which could further degrade the ecosystem.

➢ Carbon Sequestration and Coastal Protection:

The changes in mangrove species composition also impact the ecosystem services provided by the Sundarbans. Mangroves play a crucial role in carbon sequestration, and shifts toward less carbon-dense species could reduce the overall carbon storage capacity of the forest. Similarly, the ability of the mangrove ecosystem to protect coastal

areas from storm surges and erosion may be compromised as certain species that provide stronger physical barriers decline.

Climate change is driving significant and complex shifts in the species composition, distribution, and interactions within the Sundarbans mangrove ecosystem. These shifts are leading to a decline in biodiversity, altered ecological relationships, and changes in the ecosystem services that the Sundarbans provide. The cumulative effects of these changes threaten the long-term stability and resilience of the ecosystem, underscoring the need for adaptive management strategies that can help mitigate the impacts of climate change and preserve the ecological integrity of the Sundarbans.

Current and proposed adaptive management strategies aimed at mitigating the adverse effects of climate change on the Sundarbans, including community-based conservation efforts and policy interventions.

The Sundarbans, the largest mangrove forest in the world, is highly vulnerable to the impacts of climate change, including rising sea levels, increased salinity, and more frequent and intense cyclones. Various adaptive management strategies have been implemented and proposed to mitigate these adverse effects, focusing on both environmental sustainability and the well-being of local communities.

Current Adaptive Management Strategies

- **Mangrove Restoration and Afforestation:**

➢ **Reforestation Initiatives:**

Ongoing efforts involve planting mangroves in degraded areas to enhance coastal protection. These mangroves act as natural barriers against storm surges and erosion.

➢ **Biodiversity Conservation:**

Protecting the diverse flora and fauna of the Sundarbans, including endangered species like the Bengal tiger, is crucial. This includes creating buffer zones and restricting human activities in core areas.

- **Community-Based Conservation Efforts:**

➢ **Livelihood Diversification:**

To reduce dependence on natural resources, initiatives have been introduced to promote alternative livelihoods such as sustainable aquaculture, honey production, and ecotourism.

➢ **Awareness and Education Programs:**

Local communities are being educated about the impacts of climate change and the importance of conservation. Training programs on sustainable practices are being provided.

➢ **Co-Management Models:**

Collaborative management involving local communities, NGOs, and government agencies has been adopted to ensure more inclusive and effective conservation efforts.

- **Cyclone Shelters and Early Warning Systems:**

➢ **Infrastructure Development:**

Construction of cyclone shelters and elevated platforms in vulnerable areas helps protect lives during extreme weather events.

- **Improved Forecasting:**

Enhanced early warning systems and disaster preparedness plans have been implemented to reduce the risks associated with cyclones and flooding. Proposed Adaptive Management Strategies

- **Integrated Coastal Zone Management (ICZM):**

- **Holistic Approach:**

ICZM promotes the sustainable use of coastal resources by integrating environmental, socio-economic, and governance aspects. This approach aims to balance development needs with conservation efforts.

- **Policy Interventions:**

Strengthening policies related to land use, coastal zoning, and resource management is essential to mitigate the impacts of climate change on the Sundarbans.

- **Climate-Resilient Infrastructure:**

- **Resilient Housing and Infrastructure:**

Building climate-resilient homes, roads, and other infrastructure in the region to withstand extreme weather events.

- **Water Management Systems:**

Developing efficient water management systems to address increasing salinity and ensure freshwater availability for both people and agriculture.

- **Strengthening Governance and Policy Frameworks:**

- **Cross-Border Cooperation:**

Since the Sundarbans spans India and Bangladesh, enhanced cooperation between the two countries is crucial for effective management and conservation.

- **Enhanced Legal Frameworks:**

Updating and enforcing legal frameworks to protect the Sundarbans, including stricter regulations on deforestation, pollution, and illegal fishing activities.

- **Community-Based Adaptation (CBA) Initiatives:**

- **Participatory Planning:**

Involving local communities in the planning and decision-making processes ensures that adaptive strategies are tailored to their needs and knowledge.

- **Resilience Building:**

Programs aimed at building the resilience of local communities to climate change through capacity-building, financial support, and infrastructure development.

- **Research and Monitoring:**

➢ **Climate Impact Studies:**

Continuous research to monitor the impacts of climate change on the Sundarbans ecosystem and local communities, providing data for informed decision-making.

➢ **Monitoring Programs:**

Establishing long-term monitoring programs to track changes in biodiversity, water quality, and land use.

IV. CHALLENGES AND CONSIDERATIONS

➢ **Resource Constraints:**

Limited financial and technical resources pose significant challenges to implementing adaptive strategies.

➢ **Political Will and Governance:**

Effective implementation requires strong political will and governance at local, national, and international levels.

➢ **Community Engagement:**

Sustained community engagement is essential for the success of conservation efforts, but it requires addressing the immediate needs and concerns of local populations. Mitigating the adverse effects of climate change on the Sundarbans requires a multi-faceted approach that combines environmental conservation, sustainable development, and community empowerment. By integrating current efforts with proposed strategies, and addressing the challenges, it is possible to enhance the resilience of this unique and vital ecosystem.

V. CONCLUSION

The Sundarbans, one of the world's most biodiverse and ecologically important regions, is under severe threat from climate change. Rising sea levels, increasing salinity, more frequent and intense cyclones, and changes in temperature and rainfall patterns are destabilizing this delicate ecosystem. These environmental shifts are causing habitat loss, a decline in biodiversity, and greater risks for the millions of people who depend on the Sundarbans for their livelihoods and protection from coastal storms.

This analysis has shown the wide-ranging effects of climate change on the Sundarbans, including the deterioration of mangrove habitats, changes in species distribution, and heightened socio-economic vulnerability for local communities reliant on the region’s ecosystem services, such as fishing, timber, and coastal protection. The compounded effects of climate change are not only threatening the Sundarbans' ecological health but also intensifying challenges for the communities it supports.Mitigation efforts such as mangrove restoration, community-driven conservation, and the development of climate-resilient infrastructure are important but insufficient on their own. A more holistic approach is necessary—one that includes stronger governance, enhanced cooperation between Bangladesh and India, and greater involvement from local communities. These measures are vital to securing the long-term sustainability of this critical ecosystem.The Sundarbans is at the forefront of climate change’s impacts but also serves as a key example for global conservation and adaptation strategies. Protecting this unique environment is not only crucial for preserving its biodiversity and the services it provides but also for ensuring the well-being of millions of people. The future of the Sundarbans depends on coordinated, long-term actions from governments, local communities, and the global community to confront the growing threats of climate change.

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