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Thresholds and Adaptation Pathways of Nature-based Solutions for Sea-level Rise

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Abstract: Nature-based solutions serve as flexible, multi-functional, and adaptable actions aimed at promoting human well-being and socioeconomic benefits from climate risks by restoring natural ecosystem structures and functions. Due to uncertainties such as the magnitude/rate of sea-level rise (SLR), social politics, economic investment, etc., those strategies might be unfeasible and reach the tipping points of socio-ecological performance. The design of dynamic adaptation pathways contains a broad suite of actions that should be adopted in different SLR scenarios based on each method's thresholds to better manage uncertainty. The research question is, how to know the thresholds of nature-based strategies and create pathways to preserve multiple options in an uncertain future? To facilitate it, the paper defines the metrics to assess nature-based solutions' performance under SLR and unpack the thresholds of each strategy based on case study analysis of the US, to design adaptation pathways over time. Results indicated that the feasible combination of nature-based strategies/pathways could bring more socio-ecological benefits. The number of adaptation options/pathways would decline with the extreme SLR, which shows coastal adaptation needs to start earlier than expected. These findings explore alternative sequences of decisions and illuminate the paths of alternative strategies to better adapt to SLR.

Keywords: thresholds, nature-based solutions, adaptation, pathways, sea-level rise

1. Introduction

Adaptation activities may no longer operate well as time passes and ambient conditions change, resulting in adaptation tipping points [1]. Subsequently, a change in action is required to continue achieving the final goals, which are required to identify thresholds [2]. Adaptation pathways are connected sets of activities that can be done when circumstances change to support decision-making under great uncertainty (Figure 1). Despite the proven ability of adaptation pathways for policy-makers, managers, and planners to together plan in uncertain situations, they are rarely utilized [3,4,5] have applied adaptation pathways to sea-level rise in on-ground projects, but the solutions contained in their pathways mainly focus on large single-purpose engineering solutions such as raised flood walls, levee, etc. Nature-based solutions (e.g., wetlands, lagoons, marshes, mangroves, etc.) use living organisms, soils, sediments, and landscape features to reduce sea-level rise hazards are grow, evolve, and change through time and more flexible to non-stationary climate future [6], which deserves more attention for their evolution and multiple adaptation pathways design. Therefore, there are two research questions, what are the tipping points of different nature-based solutions? How to design

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nature-based adaptation pathways based on the thresholds? The motivation is to design a framework for adaptation pathways, allowing coastal managers to tailor their paths while extending planning timelines and considering path dependency and uncertainty.

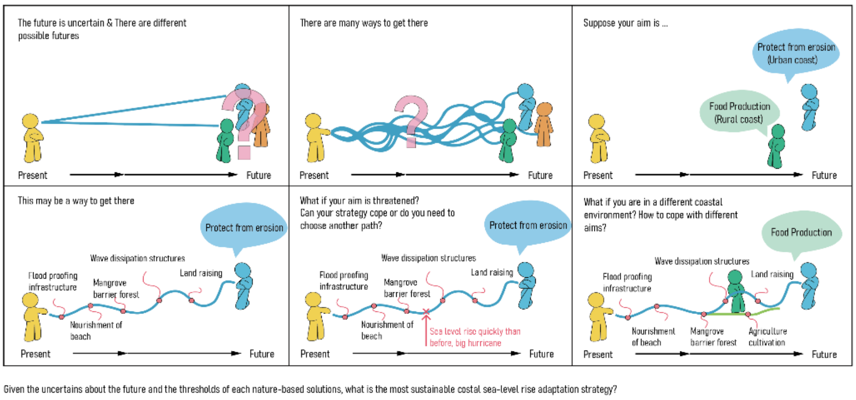

Figure 1: Sustainable coastal adaptation plan for SLR considering future uncertainties.

2. Methodology

2.1. Categorization of Nature-based Solutions

Nature-based strategies for the SLR include land raising, dunes, oyster and coral reefs, barrier islands, coastal wetlands, waterfront parks, etc. [7]. To identify multiple adaptation interventions and address their unique implications of sea-level rise, a list of six frequent and proven adaptation techniques was made (Table 1) and divided into three categories: protect, accommodate, and retreat according to the Intergovernmental Panel on Climate Change (IPCC).

Table 1: Description and categorization about nature-based solutions for SLR (Source: [2]).

Adaptation option	Description
Accommodate	Reducing the damage from flooding or SLR induced erosion
Flood proofing infrastructures	Designing, raising, retrofitting infrastructures to reduce their vulnerability.
Wetlands	Coastal wetlands environments are subject to tidal variations.
Protect	Defending areas exposed to SLR
Wave dissipation structures (oyster reefs)	Natural structures that reduce wave energy, restoration of existing wetlands where suitable conditions exist.
Beach/dunes Nourishment	Artificial addition of sediment to beach to move mean high-water seawards, reducing flooding and erosion of dryland.
Mangrove forests	Restoration of mangroves provides extra benefits such as habitat provision and carbon sequestration.
Retreat	Spontaneous or planned abandoning structures
Setback to leave room	Deliberate process of setting back the coast line where defenses were maintained. Constrained by psychological, institutional, and practical limits.

2.2. Evaluation Metrics

Identifying and implementing appropriate adaptation alternatives is a complex task [8], an adaptable coastal sea-level rise management plan should be both robust and flexible [9], meaning that it can be adapted to changing and unpredictable future conditions. However, assessments of those strategies' performance typically focus on only one type of response, and rigorous application requires accounting for social, environmental, and economic uncertainties over time [10,11]. As a result, the socio-environmental and financial metrics are defined to evaluate the thresholds that cause nature-based solutions to fail or not perform well under sea-level rise. The metrics to evaluate tipping points are as follows:

- Social effects: including social acceptability, stakeholders' evolvement, and social impacts such as green gentrification, education services, etc.
- Robustness: the extent to which a choice or policy works effectively under a variety of circumstances [12].
- Flexible: the ability for a method to change, transform, and succeed with sea-level changes [12].
- Eco-services: refers to a wide range of ecosystem services or advantages to humans, such as flood protection from storm surges, land erosion management, better water quality, fish, and shellfish species diversification.
- Material and space availability: whether there is a lack of raw materials supplies or enough space.
- Financial maintenance or implementation: economic production or services is insufficient.

Through those defined metrics, we can make a comprehensive evaluation of nature-based strategies performances and analyze their thresholds/tipping points, to generalize possible nature-based intervention adaptation pathways for SLR in US coastal cities. The developed paths are based on nature-based solutions performance under different seawater heights and tipping point circumstances (including social, economic, and environmental situations), illustrating sequences of urban adaptation possibilities as the SLR in the future. The framework and methods of research is shown in Figure 2.

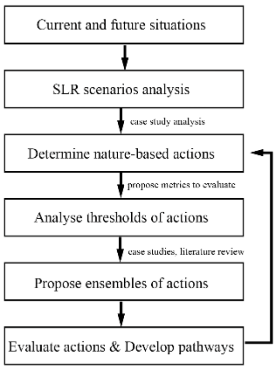

Figure 2: Research framework and research methods.

2.3. Case Studies Analysis

The research used a mixed methods approach that combines both empirical and theoretical research. In the empirical research, I examine current practices of adaptation to shed light on the performance of nature-based solutions under different SLR scenarios to know the thresholds (shown in Table 2). The thresholds are qualitatively evaluated through the metrics mentioned and defined before. This inductive research consists of two components: a review of a broader set of recent adaptation plans from the US and in-depth case study research of flood-prone cities in the US. Those case studies lie in the most vulnerable states when suffering floods in the US, which are New York, Massachusetts,

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Virginia, California, Florida, and South Carolina. This research reviewed approximately ten documents for each case study overall nearly fifty documents in total to inform the case study research and get a better understanding of nature-based practices under SLR in each of the cities. Documents include planning documents, adaptation strategies, technical reports, and government publications at a range of scales. I use the empirical research to propose several adaptation pathways and a set of actionable recommendations for planners and decision-makers under different SLR scenarios. This research could be improved with more supportive nature-based solutions performance data and more case studies analysis under different geographical coastal contexts in the US. The actual nature-based case studies are listed below:

- Oyster reefs: Chesapeake Bay (MA), Gowanus Canal in Brooklyn (NY).
- Mangroves: The Great Marsh (MA), Key West (FL).
- Wetlands: Hudson River (NY), San Pablo Bay National Wildlife Refuge (CA).
- Waterfront parks: Battery Park (NY), Brooklyn Park (NY), Piers Park (MA).
- Sand Dunes: Virginia Beach (VA), Withers Estuary in Myrtle Beach (SC).

3. Unpacking the Thresholds of Nature-based Solutions

Tipping points of nature-based solutions are caused by a variety of reasons, including material and space availability, social acceptability, financial maintenance or implementation, robustness, flexibility, eco-services, etc. The thresholds of each nature-based option are analyzed in terms of its ability to mitigate the most significant sea-level rise consequences on coastal systems (Table 2). The metrics that would affect the performance of each option are listed in the chart and concluded from case studies analysis and documentation review of those cases.

Table 2: Thresholds for nature-based solutions [Source: 2, 5, 7, 15].

Adaptation option	Influence metrics	Thresholds description
Accommodate		
Flood-proofing infrastructures (Land raising, waterfront parks)	Financial Flexible Space and material	Hard to change the typography to make it adaptable to SLR. Expensive costs for construction.
Wetlands	Financial Robustness	Habitats need space to migrate upland, which is a challenge in highly urbanized areas. Lead-in time for the new wetland formation.
Protect		
Wave dissipation structures (oyster reefs)	Financial Eco-services	Expensive costs of with compliable structure in order to form marine habitats.
Beach/dunes Nourishment	Material and space Social effects Flexible	Need sand resources and coastal space for sand succession. Unexpected frequency of sea-level rise would affect performance.
Mangrove forests	Eco-services Robustness	Vulnerable to extreme weather conditions, high tidal speeds, high salinity, and sediments.
Retreat		
Setback to leave room	Social effects Financial	Shoreline may loss the opportunity for tourism, economic income. ecological values, etc.

From a theoretical point of view, it is hard to determine the exact point that those nature-based systems would fail or permanently inundated or no longer provide ecosystem services and protective services, given the scenarios of SLR and the great uncertainty of coastal management, socio-economic and climatologic scenarios [13]. And sometimes there is no need to determine the tipping points. For example, the beach nourishment strategy is intrinsically flexible: the volume of sand supplied can be enlarged or decreased depending on the rate of SLR. In that case, it is not possible and not necessary to determine tipping points. It is likely that the combination of sediment input and sea level rise rates, as well as location-specific above and below-ground productivity and the frequency of events (e.g., storms) that remove or resuspend deposited materials, ultimately determine the ability of nature-based solutions to keep pace with SLR in different locations. From a practical point of view, future research is needed to find alternative approaches for distilling the performance data for each method over time. This might be accomplished by combining data-driven detection of changes in observed events with scenarios and modeling exploration of probable future occurrences [14].

4. Nature-based Adaptation Pathways for Sea-level Rise

This paper chose to analyze the SLR adaptation plans and nature-based solutions proposed under multiple SLR scenarios of places like the former case studies (shown in Table 3). All those plans for SLR mentioned the importance of phased adaptation, which allows managers to undertake adaptation incrementally to allow time for long-term planning and encourages the use of ecological and physical strategies and processes to protect inland, backshore environment while preserving coastal resources.

Table 3: Overview of reviewed SLR adaptation plan of case studies.

Site/City /State	Plan	Nature-based Solutions under different SLR
New York (NY)	Lower Manhattan Coastal Resiliency	Current (0-0.8m): land raising, green infrastructure, wetlands.
		Future (> 0.8m): multilevel waterfront parks, retreat.
San Diego Bay (CA)	Sea Level Rise Adaptation Strategy for San Diego Bay, California	Current (0-0.8m): protect current beach, wetlands.
		Future (> 0.8m): hybrid armouring approach, marsh sills, buried revetments and cobble berms.
Boston (MA)	Climate Ready Boston	Current (0-0.8m): add green infrastructures, upgrade drainage systems.
		Future (> 0.8m): land raising, waterfront park systems, retreat
Virginia Beach (VA)	Virginia Beach Sea Level Wise Adaptation Strategy	Current (0-0.8m): land raising, integrated blue-green infrastructures, mangroves.
		Future (> 0.8m): wetland green corridors.
Miami (FL)	Miami-Dade County, Florida: Sea Level Rise Strategy	Current (0-0.8m): expand greenways and blueways, waterfront parks and green infrastructures.
		Future (> 0.8m): expand mangroves, beaches, dunes.
Charleston (SC)	Sea Level Rise Adaptation and Mitigation Planning in Charleston, South Carolina	Current (0-0.8m): coastal agriculture, green infrastructures.
		Future (> 0.8m): regional SLR defence, large-scale moveable sand dunes together with moveable wetlands as segments.

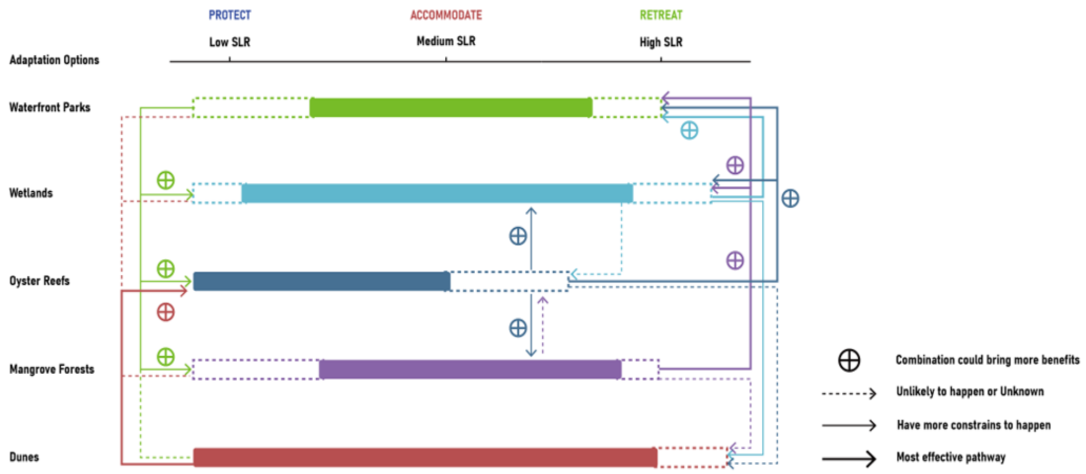

Figure 3: Nature-based adaptation paths for SLR [Source: 2].

Note: The colored boxes evaluated the SLR according to three categories: low (less than 0.3 m), medium (0.3–0.8 m), and high (more than 0.8 m). The length of colored boxes presents the human services (protect or accommodate) that methods could serve.

Under the low and medium SLR scenario, there are multiple nature-based adaptation pathways to be chosen. The most effective one is to gradually establish mangroves and wetlands to create a soft edge and increase species richness. To enhance the robustness of this pathway, we can combine it with the oyster reefs construction, which could better form wave attenuation structures with natural analogs, decreasing the morphological change due to storm surge and wave action [15] and link the advantages of different methods to achieve the highest ecological and human protective benefits. With such a combination, the resulting calmer seawaters can ensure the formation of coastal salt marshes and seagrass beds, which create a highly beneficial type of natural coastal and wetland protection. But it only makes the wetlands systems in dynamic equilibrium with short-term moderate fluctuations in SLR, with a huge drop in effectiveness during extreme flooding. And a higher rate of SLR could make the plants intolerant to salt, which takes a long time to rebuild and return to balance, and hard to attain maximum targeted performance under the context of the larger spatial environment [16,17]. The reviewed SLR adaptation plans of Florida and New York show that strategically situated and frequently narrow wetlands or mangrove fringes may only contribute to a small portion of the nutrients fluxing from landward watersheds [18]. Another pathway is to build waterfront parks and blue-green infrastructures, which mainly rely on the construction of hard protective infrastructure and land elevation and always happen in highly urbanized cities. But we should know that it only lasts a short amount of time and mainly serves as human protection method, and we must migrate or retreat if we do not consider other methods. Thirdly, dunes could reduce flood risks by adding sediment to the beach system while reducing the impact on shoreline systems in existing sand-rich beaches. The adaptation pathways to nourish dunes could start with low and medium SLR to prepare for the future high-water level.

Under the high SLR scenario, the effective pathway is to build dunes, which would take a long time depending on the shorelines sediment trap effectiveness, wetland elevation, tidal range, and local sea-level rise rates, and it only succeeded in coastal areas with abundant sediment supplies [19]. The reviewed SLR adaptation plans of Virginia Beach and Miami show that fixed dunes are vulnerable to sea-level rise, but the movable dunes could be more adaptative to dynamic water levels. Besides, dune restoration could combine with the wetland’s formation, which in Miami used sand fencing to trap sand and construct new dunes, in conjunction with planting suitable beach grass species to retain the sand in place, enhancing accretion and limited erosion [20]. Another pathway under extremely high SLR is to build regional multilevel waterfront parks to defend SLR in larger-spatial contexts, and finally, setback, retreat and leave room for the coastal shorelines.

Aside from the uncertainty of SLR scenarios, socioeconomic changes may have an impact on the pathway's effectiveness [21]. First, some methods may become unavailable due to social-economic constraints. For example, socioeconomic developments and coastal shoreline moderation may result in extra spatial demands, leaving no room for dunes or wetlands methods. Second, there are trade-offs and combinations among different adaptation pathways due to policy goals, costs/investments, or other socioeconomic issues. For example, if we use oyster reefs as a potential pathway, enhancing their current resilience will increase the sunk-cost effects and social-economic vulnerability in less developed coastal areas [22]. Similarly, if we chose dunes as remedies for pathways, we also need to acknowledge the trade-off between the larger costs of ongoing nourishment and the stronger modification of the coastline and social acceptability [23]. The nourishment volumes would increase as the sea-level rise, which is unpalatable to inhabitants, tourists, and the environment. Finally, there are more complex SLR scenarios considering the geographical and social differences to larger spatial extents. The actual pathways for specific site conditions require separate research, showing different adaptation goals, and measures.

5. Conclusions

Exploring nature-based adaptation pathways to continuing SLR can assist planners in determining the viability and sustainability of coastal adaptation in the face of uncertainty. A better understanding of the tipping points for those methods could lead us to make a combination and retrofit multiple methods in the long-term sea-level rise adaptation management [2]. Researching those pathways and monitoring for adaptive signals becomes increasingly important as sea-level rise accelerates because some are not workable due to social-economic, space limitations, water level, sediment, geography restrictions, etc. The research indicates that the combination of nature-based solutions to form pathways is more efficient and robust than a single strategy. Considering the high uncertainty of SLR, coastal areas should start the adaptation planning through the pathway analysis earlier, which requires a larger time-consuming combination or replacement of methods. The priority is to protect urban environments through soft measures, especially through large-scale waterfront parks, wetlands, and dunes. In the long run, if the seawater level continues to rise and flooding becomes permanent, planners will be forced to raise the land continually or use large-scale engineering methods (flood gate, raised flood wall, levee, etc.) and finally retreat. With different adaptation pathways as potential choices for sea-level rise management, such a multi-pronged approach opens more possibilities.

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