

Advancing Coastal Resilience: Scenario-Based Optimization of Nature-Based Solutions

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Coastal erosion, caused by extreme weather events such as storms, poses a major risk to the sustainability of estuarine and coastal shorelines. Storm surges, driven by intense winds and low atmospheric pressure, can rapidly raise sea levels, leading to severe inundation and increased erosion along vulnerable coastlines. Addressing these challenges requires innovative and sustainable approaches that go beyond traditional engineered defenses.

Nature-Based Solutions (NBS) for coastal protection are strategies that utilize natural ecosystems to protect coastal environments from erosion, flooding, and other environmental challenges. These solutions act as natural barriers, reduce wave energy and stabilize shorelines. In contrast to traditional engineered coastal defense systems, NBS provide sustainable, cost-effective, and resilient alternatives. Furthermore, they provide additional benefits such as new habitat creation for coastal organisms, carbon sequestration, and improved water quality. Seagrass meadows or mangrove trees, in particular, act as natural wave dampers, interfering with coastal wave processes and significantly lowering wave heights, which reduces the impact of wave-induced stress on shorelines.

This study employs an integrated modeling framework to conduct "What-If" Scenarios (WiS) for evaluating the effectiveness of vegetation as a coastal protection measure. The framework combines a regional hydrodynamic-waves-sediment model with the morphodynamic model XBeach to simulate storm impacts and nearshore morphological changes. Using different coastal areas (e.g. within the German Bight or Black Sea, Ghana Coast), the scenarios explore different configurations of seagrass meadows or mangroves to determine optimal strategies for erosion reduction.

The analysis highlights the importance of selecting appropriate planting depths, meadow density, and stem height to maximize the protective benefits of NBS. Results indicate that the placement of meadows, rather than simply maximizing their size, plays a critical role in mitigating erosion. Strategic adjustments in planting design, based on storm characteristics and local bathymetry, can significantly enhance the efficiency of sediment stabilization, reducing erosion risks across varying conditions. This work demonstrates the value of Digital Twin-based What-If Scenarios for guiding the design and implementation of NBS. By simulating different configurations and environmental conditions, the approach fosters data-driven decision-making and collaborative planning among stakeholders. The findings provide actionable insights for coastal managers and policymakers, supporting the broader adoption of NBS as a viable strategy for enhancing coastal resilience and adapting to the growing impacts of climate change.