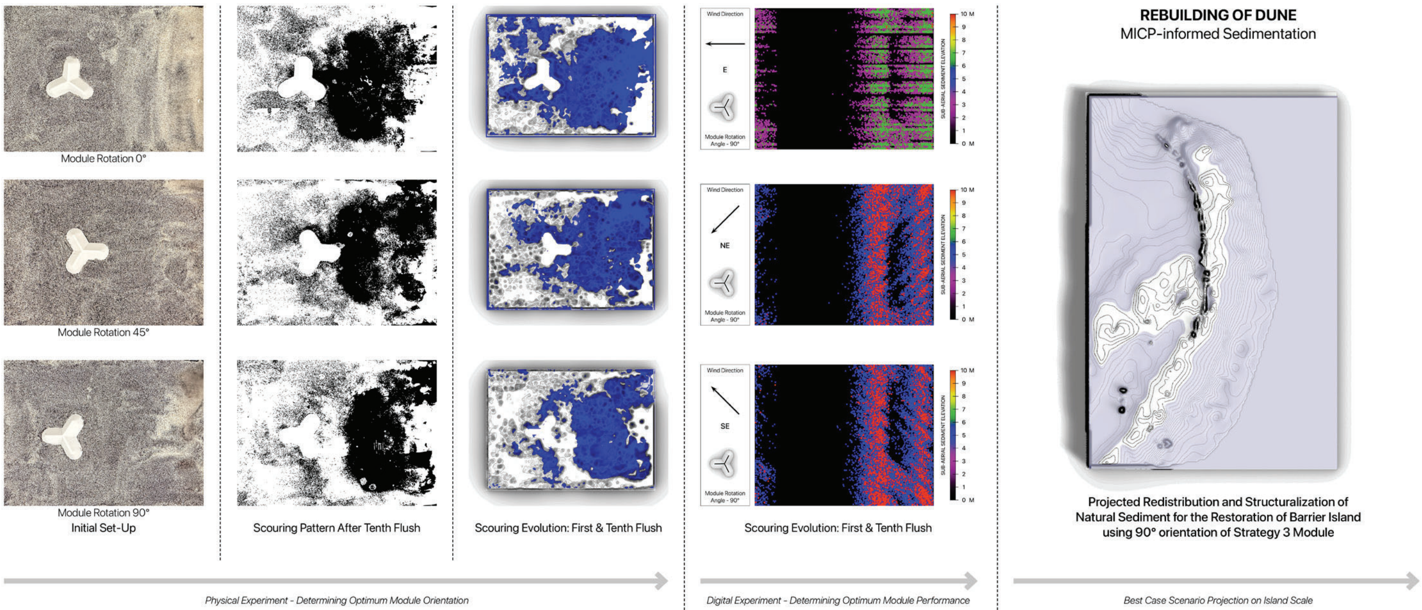
Regenerative Terrain Shaping for Barrier Island Resilience

MICP-informed Sedimentation Approach to Louisiana's Chandeleur Islands

Khevna Modi
Carnegie Mellon University

Dana Cupkova
Carnegie Mellon University

Christine Mondor
Carnegie Mellon University



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1 Guided sedimentation - computational processing of simulation test bed and terrain simulation analysis.

ABSTRACT

Barrier islands protect coastlines from storms and sea level rise, but face increasing threats from climate change. Since 1998, hurricanes and environmental hazards, including major oil spills, have accelerated erosion along Louisiana's coast, leading to severe land loss and the degradation of fragile barrier islands. Current land restoration methods often favor carbon-intensive strategies to alter the morphology of the landform. Microbially induced calcium carbonate precipitation (MICP) offers an alternative to high-carbon, terrain-based alterations and, when combined with natural sedimentation trends, provides new opportunities for low-carbon ecosystem resilience.

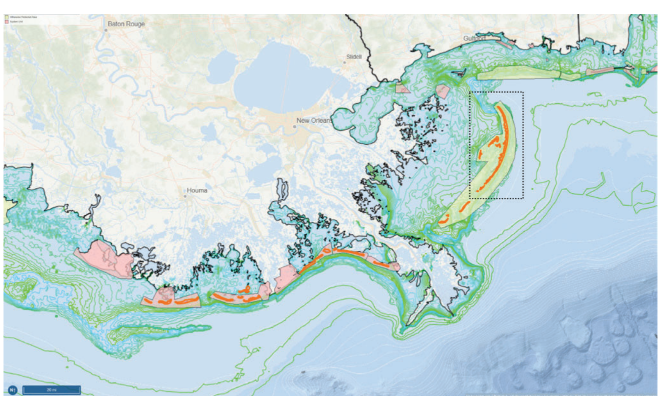
This computational study explores a regenerative terrain strategy that directs sediment transport and studies mitigating erosion by minimally applying MICP to reinforce coastal soils, enabling adaptive land building and recovery through coupled sedimentation and MICP structuralization. Our mixed-methods simulation approach combines computational analysis with physical simulation, drawing on two decades of geomorphological data, to analyze erosion patterns and land transformation that could advance ecological reciprocity informed by large-scale MICP studies. Spatial vulnerability mapping via ArcGIS informs MICP-based dune system setups, which are simulated using Docofossor and DuneWorm Grasshopper plug-ins to model sediment movement under varying computational fluid dynamics-driven wave energies. This framework is tested using sand and wave simulations, with visual data processed through image depth mapping to track volumetric change.

Summary results evaluate the effectiveness of varied dune patterns across prevailing wind directions, indicating a strategic approach to island form restoration. This computational setup demonstrates the potential of selective, minimal-impact MICP application for land structuralization through dune accretion, offering a low-carbon, adaptive, and scalable solution for restoring barrier islands in the face of climate change.

INTRODUCTION

This research study investigates the erosion patterns of the Chandeleur Islands (Fig. 2) and how a better understanding of geomorphological processes can augment restoration efforts. It explores how sediment migration and historical events inform effective intervention zones and terrain shaping to stabilize soils and support postdisturbance recovery. By integrating computational modeling with living systems thinking, the project contributes to discourse on climate adaptation and resilience, demonstrating how digital tools and ecological data can foster regenerative, nonanthropocentric design strategies. The hypothesis is that microbially induced calcium carbonate precipitation (MICP)-induced terrain patterns, guided by computational simulation (Roy, Cupkova, and Mondor 2024), can inform sediment transport (Hurkxkens et al. 2021) and thus enhance island resilience by improving soil stabilization and optimizing sediment accumulation, reducing reliance on carbon-intensive methods and promoting long-term ecological stability (USGS, n.d.; Self-Assembly Lab, n.d.).

Louisiana's Gulf Coast, particularly the New Orleans region, is increasingly vulnerable to sea-level rise, intensified storms, and disrupted sediment flows. Frequent flooding, land loss, and saltwater intrusion continue to pressure coastal communities and ecosystems. Barrier islands, which buffer storm surge and wave energy, are rapidly degrading due to climate change, shrinking in landmass and ecological function (Zinnert et al. 2017). The Chandeleur Islands have lost over 40% of their area in the past century, with shoreline retreat reaching up to 149 feet per year between 2004 and 2012 (Byrnes et al. 2018, 2).



2 Extracted map of the Gulf of Mexico's barrier island system, with emphasis on the Northern Chandeleur Islands along the Louisiana coastline ("Environmental Response Management Application (ERMA) - Gulf of Mexico," n.d.)

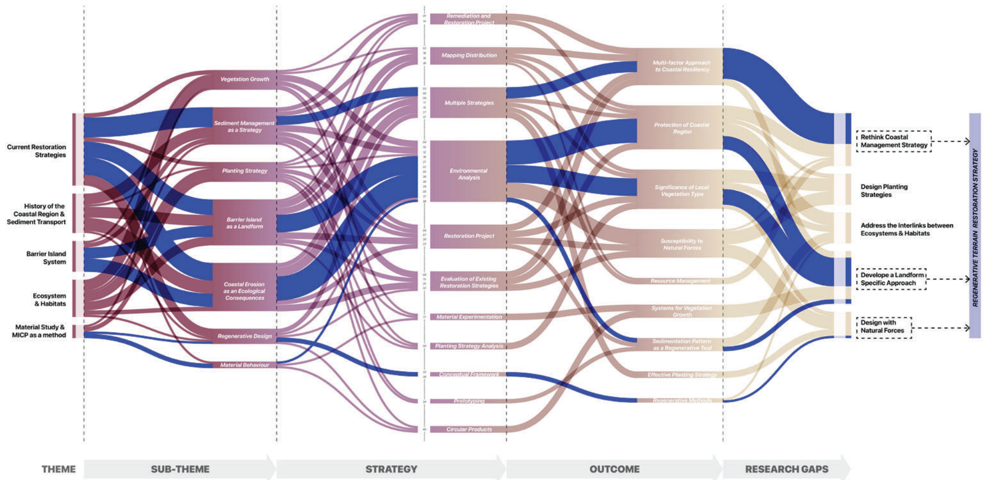
These losses are both physical and ecological. As barrier islands erode, back-barrier ecosystems, such as marshes and lagoons, lose their protective buffer, leaving inland wetlands and mainland areas exposed to Gulf forces. This increased exposure heightens wave energy, storm surges, salinity intrusion, and tidal fluctuations, accelerating wetland collapse (USGS, n.d.). Public restoration efforts have largely focused on human-centered goals such as disaster mitigation and recreation, often overlooking the ecological agency of nonhuman systems. However, some designers and conservationists are integrating natural systems into regenerative practices using fabrication methods, computational tools, and environmental simulations (Hurkxkens et al. 2021; Self-Assembly Lab, n.d.).

Drawing on Jane Bennett's (2010) concept of nonhuman agency and Bill Reed's model of living systems design (Mang and Reed 2013), this work critiques anthropocentric restoration and proposes an alternative grounded in coexistence and ecosystem reciprocity. It argues for coastal interventions that align with geomorphic processes (Cantrell, Martin, and Ellis 2017; Duong 2023), enabling adaptive, self-regenerative recovery. In this context, computational thinking is essential, not just for simulating dynamic systems but for embedding resilience into terrain design. By combining emerging computational methods with biotechnical frameworks for sediment structuralization, such as MICP, the project investigates terrain-based strategies that couple climate-responsive modeling with low-impact, performance-driven fabrication.

STATE OF THE ART

Barrier islands are dynamic landforms shaped by wind, waves, and longshore currents. Composed mainly of sand and sediment, they buffer mainland areas from storms while supporting diverse ecosystems like dunes and salt marshes. Despite their protective role, barrier islands are vulnerable to rapid erosion and storm-induced retreat (How Things Work 1970).

The Chandeleur Islands exemplify sediment-driven transformation. After the Mississippi River shifted to the Lafourche lobe, reduced sediment supply altered their geomorphic trajectory, and northern areas became stage two transgressive barrier arcs while southern portions evolved into stage-three inner shelf shoals (Fitzgerald et al. 2015). Indicators such as beach ridge offsets and shoreline



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3 Literature review diagram

4 Methodology diagram consisting of Phase 1: Site Analysis; Phase 2: Simulation Set-up; Phase 3: Comparative Evaluation.

change maps highlight this phased evolution, informing restoration strategies that align with the islands' dynamic sedimentary history.

Storm-induced erosion unfolds in stages—from dune scouring to overwash and full submergence—driven by storm surge height and beach-dune stability. While extreme events erode landforms, they also create new depositional features like washover fans and sheetwash terraces, reshaping coastal terrains and potentially aiding ecological succession (Kindinger et al. 2013). The Chandeleur Islands, exposed to frequent hurricanes and active longshore sediment transport, reflect this dual dynamic of erosion and reconstruction. Recognizing these opposing forces is key to designing adaptive restoration strategies.

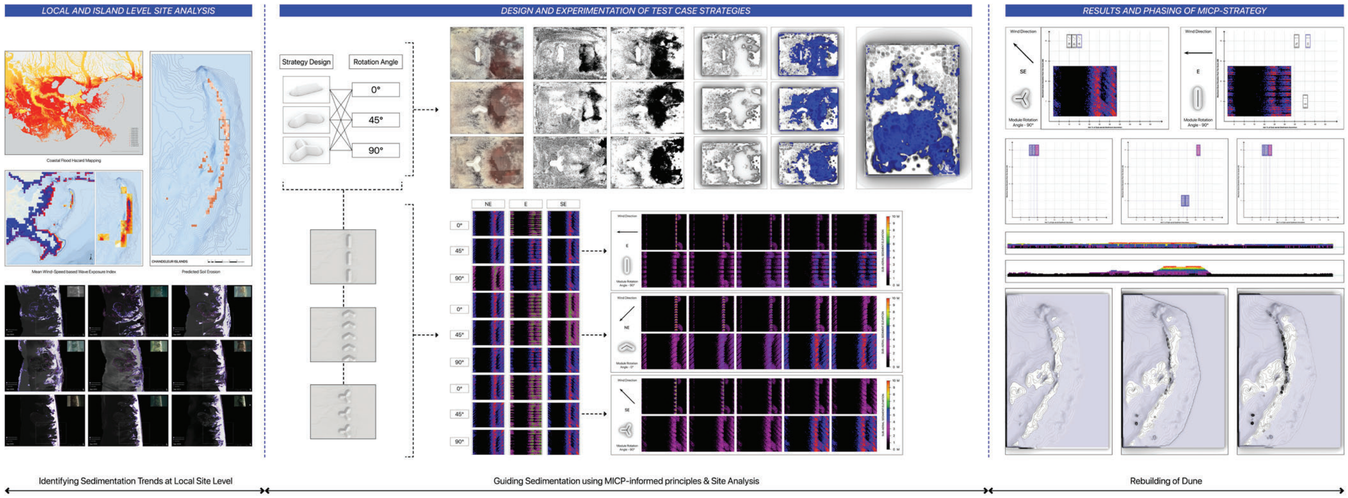
The Chandeleur Islands trace their origins to the abandoned St. Bernard delta lobe, transforming into a barrier arc as sediment supply declined and subsidence increased (Miner et al. 2021). Distinct zones exhibit varied erosion and retention patterns, with the central section experiencing the greatest land loss. In contrast, northern back-barrier areas support resilient vegetation like Spartina alterniflora and Avicennia germinans, forming marsh platforms that anchor and stabilize the shoreline.

Preservation efforts combine hard and soft engineering methods—beach nourishment, fencing, vegetation, and dredging. Initiatives such as Restore the Mississippi River Delta and the NRDA-funded Outer Coast Restoration illustrate integrated approaches that stabilize landforms while supporting ecological habitats (Johnson, n.d.; Coastal Protection and Restoration Authority of Louisiana 2023). These strategies highlight the importance of integrating sediment management with habitat restoration.

Longshore sediment transport, driven by oblique wave action, significantly shapes barrier island morphology. In these islands, this process varies seasonally: Winter fronts cause net sediment loss, while hurricane seasons contribute more constructive inputs. The central island segment faces persistent erosion, emphasizing the need for restoration strategies that enhance sediment retention. Sites like Hewes Point, identified through 20-year wind-wave modeling, lie within sediment divergence zones and offer ideal locations for targeted sand placement (USGS 2009). Aligning interventions with natural sediment flows can mitigate erosion and support long-term resilience.

Ecological outcomes of sediment placement depend on material traits—grain size, elevation, and distribution—all of which affect habitat suitability (Reed, Hijuelos, and Fearnley 2012). Without alignment to site-specific geotechnical conditions, restoration efforts may be counterproductive. Adaptive strategies must integrate ecosystem feedback to ensure long-term resilience.

Amid sediment scarcity and rising erosion, biologically driven methods like MICP present viable alternatives. Using microorganisms to bond sand grains with calcite, MICP enhances cohesion and shear strength. MICP is applied by introducing urease-producing bacteria (e.g., Sporosarcina pasteurii) along with urea and calcium chloride into sandy soils via surface spraying, percolation, or injection. At the landscape or pilot scale, this biocementation process reduces permeability. It binds loose sediments by precipitating calcium carbonate between particles, offering a nature-based approach to stabilize dune systems and mitigate coastal erosion (Osinubi et al., n.d.). For the treatment of coastal soils using the injection method, field and lab studies report significant erosion reduction: Tsai et al. (2022) found optimal results at 60–80 cm injection



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spacing; Liu et al. (2021) noted a 77% reduction on treated slopes; Tsai et al. (2022) highlighted two-phase injections for uniform strengthening.

This paper integrates environmental data patterns with computational simulation methods in landscape architecture to explore sustainable approaches to landform generation. It presents a framework for a resilient alternative to conventional engineering, supporting ecological health and sediment retention in ways that can be tailored to specific geomorphic contexts. As climate uncertainties grow, adaptive, site-specific technologies like these will be critical for redefining restoration strategies for vulnerable coastal systems such as the Chandeleur Islands.

METHODOLOGY OVERVIEW

The methodology is structured in three phases (Fig. 4). The first phase centers on coastal context site analysis, examining the island's relationship to the mainland using ArcGIS and existing datasets. Layers such as wave exposure, predicted soil erosion, coastal flood zones, and historical storm events since 2004 help identify critical areas of focus.

In the second phase, image trace mapping of selected regions reveals how past events have influenced sedimentation patterns. These patterns inform terrain design strategies that integrate the MICP injection method to regenerate simulated terrain. The Docofossor tool in Grasshopper is used to simulate dune formation through natural processes, with additional modeling using DuneWorm (Grasshopper) to test configurations under varying computational fluid dynamic-simulated wave directions. These simulations evaluate subaerial sediment volume and wave-induced scouring around dunes, providing insights into erosion and deposition dynamics.

The third and final phase evaluates the potential of MICP treatment, drawing on literature reviews, pattern studies, and dune geometries to determine which configurations perform best under shifting dynamic conditions, particularly longshore influences. These effective strategies are then projected at the island scale to assess their broader impact, contributing to informed, landscape-scale restoration planning.

PHASE ONE: SITE ANALYSIS

Coastal Context Site Analysis – Chronology of Events

Building on the literature review and site-scale studies, this phase uses geospatial data to assess key factors influencing the Chandeleur Islands, including flood exposure, wave action, land degradation, and ecological sensitivity. Synthesizing these factors will help assess vulnerable areas and provide a context for computationally testing MICP interventions.

The NOAA Coastal Flood Exposure Mapper from the ERMA–Gulf of America platform is central to this analysis. It visualizes 10 overlapping flood hazard zones—including FEMA flood zones, SLOSH storm surge projections (Category 1–3 hurricanes), and sea level rise scenarios—providing a comprehensive view of regional flood vulnerability (Fig. 5). The Chandeleur Islands fall within zones 1, 2, and 3, confirming their high exposure.

Wave action is another major driver of barrier island change. A wave exposure index, derived from wind speed exceedance and direction data developed under NOAA's Deepwater Horizon NRDA, quantifies coastal exposure to wind-driven wave energy (Fig. 6). The map reveals that the southern islands and parts of the northern chain experience the highest exposure (index > 9500), suggesting these areas should be prioritized for dune restoration and terrain strategies.

To assess land degradation, the ICRAF Soil Erosion Prevalence dataset (2002–2020) uses satellite and machine learning to predict erosion severity globally (Fig. 7). It identifies hotspots on the Chandeleur Islands where over 50% of the land surface is eroding, patterns that correspond with high wave exposure zones and confirm long-term vulnerability.

The NOAA Environmental Sensitivity Index (ESI) shoreline rankings add an ecological dimension to this analysis (Fig. 8). Shorelines are ranked from 1 (least sensitive) to 10 (most sensitive, e.g., tidal flats and marshes). Much of the Chandeleur shoreline ranks 8–10, highlighting ecologically fragile areas that are difficult to restore after disturbance. Overlaying these datasets reveals convergence zones where flood risk, wave energy, erosion, and ecological sensitivity are all high. These priority areas guide terrain simulations and design interventions in this study.

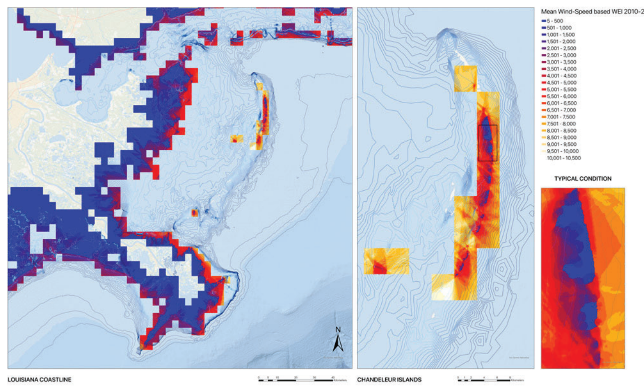
Localized Analysis – Satellite Image Mapping

Satellite imagery from 2004–2024 shows a steady decline in subaerial landmass. Hurricane Katrina (2005) created multiple tidal inlets, the 2010 Deepwater Horizon spill left visible oil trails and land loss, and Hurricane Isaac (2013) likely caused overwash conditions.

Using GIS analysis, reports, and Google Earth imagery, we identified three key regions: one central and two southern. The southernmost near Grand Gosier Shoal shows recurring ephemeral islands, while another lies near Curlew Shoals. Literature highlights the central northern chain as the most erosion-prone, and this study focuses there for targeted design intervention. Site analysis reveals high vulnerability to wind-driven wave erosion, with Google Earth imagery showing ~250 m of shoreline retreat and significant land loss between 2004 and 2024 (Fig. 10). These findings underscore the potential of regenerative, sediment-based strategies to promote natural dune formation. The following sections outline dune development and performance testing.

Phase Two: Simulation Setup

Site analysis and literature suggest aligning terrain patterning with the island's natural morphology (Fig. 11). Studies recommend placing sand deposits in the back-barrier zone at intervals perpendicular to the shoreline to facilitate redistribution through longshore drift (Miner et al. 2021). Patterns are designed to improve sediment retention and reduce transport toward Hewes Point during winter cold fronts. MICP principles inform the strategy, employing a linear surface spray injection pattern at 100 cm intervals (Tsai et al. 2022), drawing inspiration from



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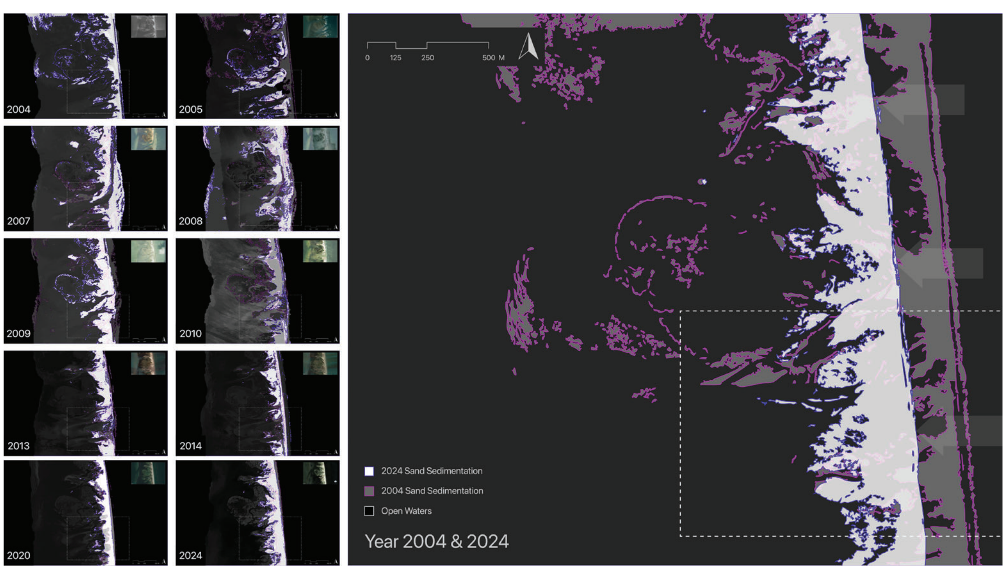

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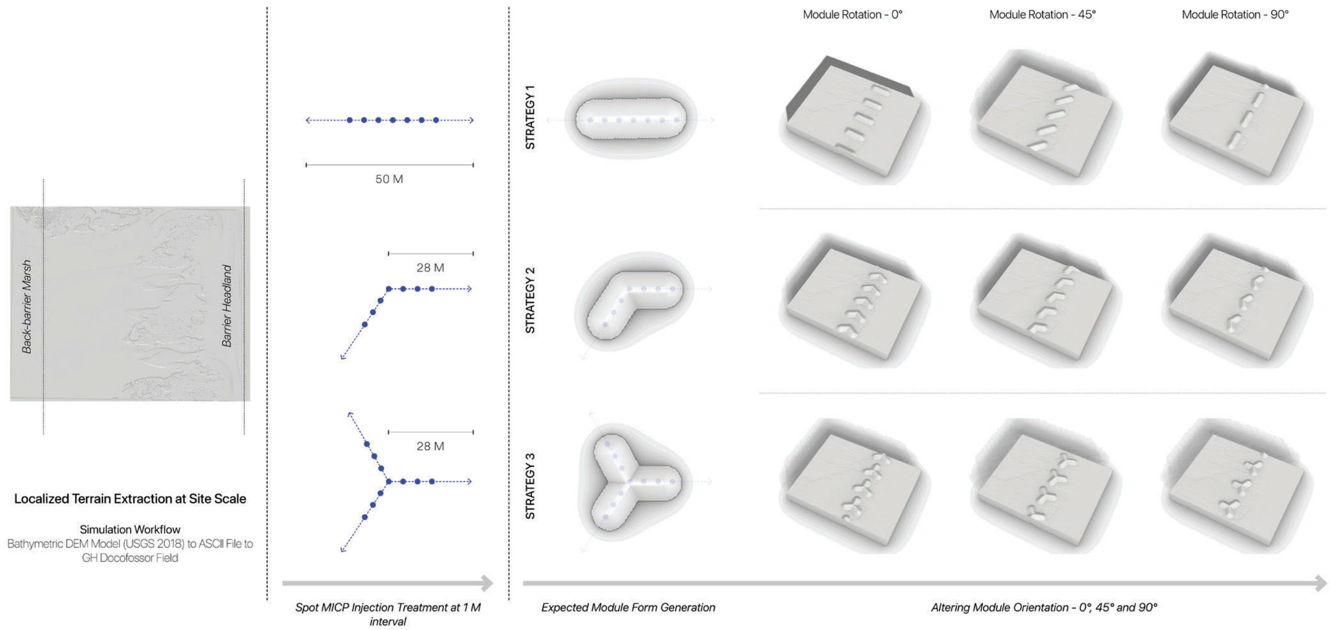
5 Mean Wave Exposure Index (2010–2011), derived from wind speed exceedance and directional exposure, mapped Chandeleur Island zones most susceptible to storm-driven change (ERMA, n.d.).

6 Sequential shoreline shift showing a landward retreat of approximately 250 meters between 2004 and 2024, mapped using satellite imaging



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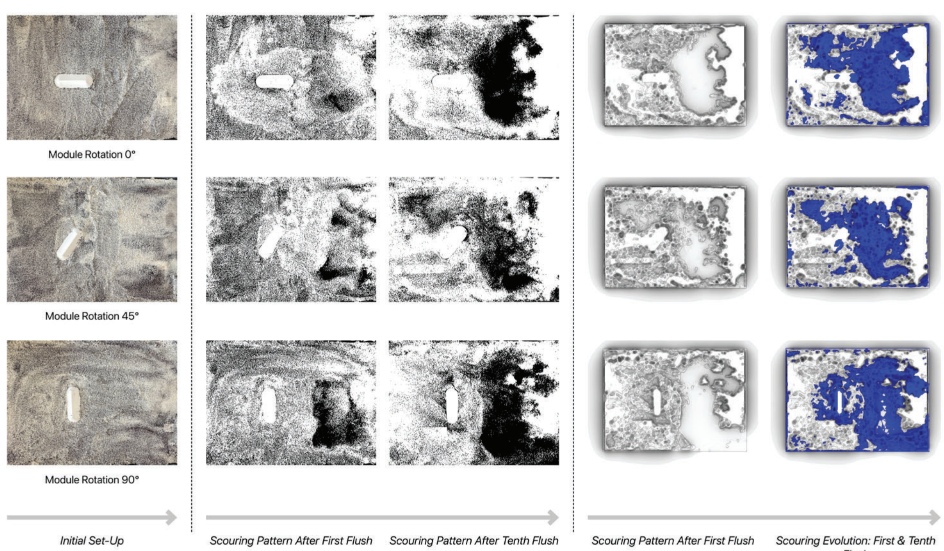
projects like Shifting Sands (Hurkxkens et al. 2021), which used robotic arms to shape terrains and reduce wave energy. Intervention placement is guided by wave exposure indices and wind data, situating MICP-treated zones between the barrier headland and back-barrier marsh. This reduces wave-induced sediment loss, supports controlled retreat, and enables headland regeneration through phased treatments.

Simulation Method: Grasshopper Docofossor and DuneWorm

This phase of the study focuses on shaping terrain within the selected local region by simulating the effects of various MICP-treatment configurations over one year to evaluate dune formation and resilience to wind-driven wave action. The base terrain model is derived from a 2018 Bathymetric DEM sourced from USGS Earth Explorer, converted to an ASCII file using ArcGIS Pro. This file is imported into Grasshopper, and the area of interest is defined by cropping the island extent with a curve input.

To simulate wind-induced wave effects over strategic dune structuralization, a linear application strategy is assumed to guide the sizing and pattern distribution of the assumed MICP injection pattern. Dunes ranging from 28 to 50 m in length are modeled, based on 100 cm injection intervals. Three module types—single-legged, two-legged, and three-legged—are created to test form variations. Each is rotated



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7 Graphical representation of MICP-injection terrain shaping patterns: single-leg (50 m) and two-/three-leg (28 m) configurations, each tested at 0°, 45°, and 90° rotations (point counts shown for reference).

8 Scouring analysis of module rotations (0°, 45°, 90°) across all strategies using sand simulations and depth-map processing; contours compare terrain after first and tenth flush to visualize erosion progression.

at 0°, 45°, and 90° to assess how orientation affects terrain resilience under wave impact.

These modules are sculpted using the Cut and Fill in Path tool within Docofossor, allowing direct terrain modeling in Grasshopper. Dunes are assigned a maximum height of 10 m and a slope angle of 35°, an intentional exaggeration used for simulation clarity and comparative analysis.

Terrain modules are tested against three prevailing wind directions—northeast, east, and southeast (Fig. 4.2.4)—to evaluate resistance to wind-driven wave action. Simulations use Grasshopper-generated 3D point clouds with defined wind vectors, tracking sediment displacement over 10 time steps. Performance is measured by percentage change in subaerial elevation and dune height to identify the most resilient configurations.

Physical Experiment: Sand Displacement Simulation and Image Processing

To complement digital simulations, a physical sand displacement experiment was conducted using two 36 in × 24 in tubs adapted from prior studies (Duong 2023; Roy 2024). One tub contained a simulation sand mix representing a barrier island section, and the other held water for circulation. A solar-powered pump and PVC piping created a controlled water flow. Water was flushed over 10 discharge cycles to visualize erosion and deposition of four kinds of colored sand particles, each with varying sizes.

Wind Direction	Module Rotation Angle	Sediment Above Baseline: Step 0	Sediment Above Baseline: Step 10	Dune Elevation Post-Ten Gusts (M)	Percentage of Net Accretion
NE	0°	1711	1897	10	9.80%
NE	45°	1518	1760	10	13.75%
NE	90°	1722	1904	7	9.56%
E	0°	1598	2726	7	41.38%
E	45°	1986	3099	10	35.91%
E	90°	1546	2696	10	42.66%
SE	0°	1696	1893	10	10.41%
SE	45°	1613	1855	10	13.05%
SE	90°	1683	1934	10	12.98%

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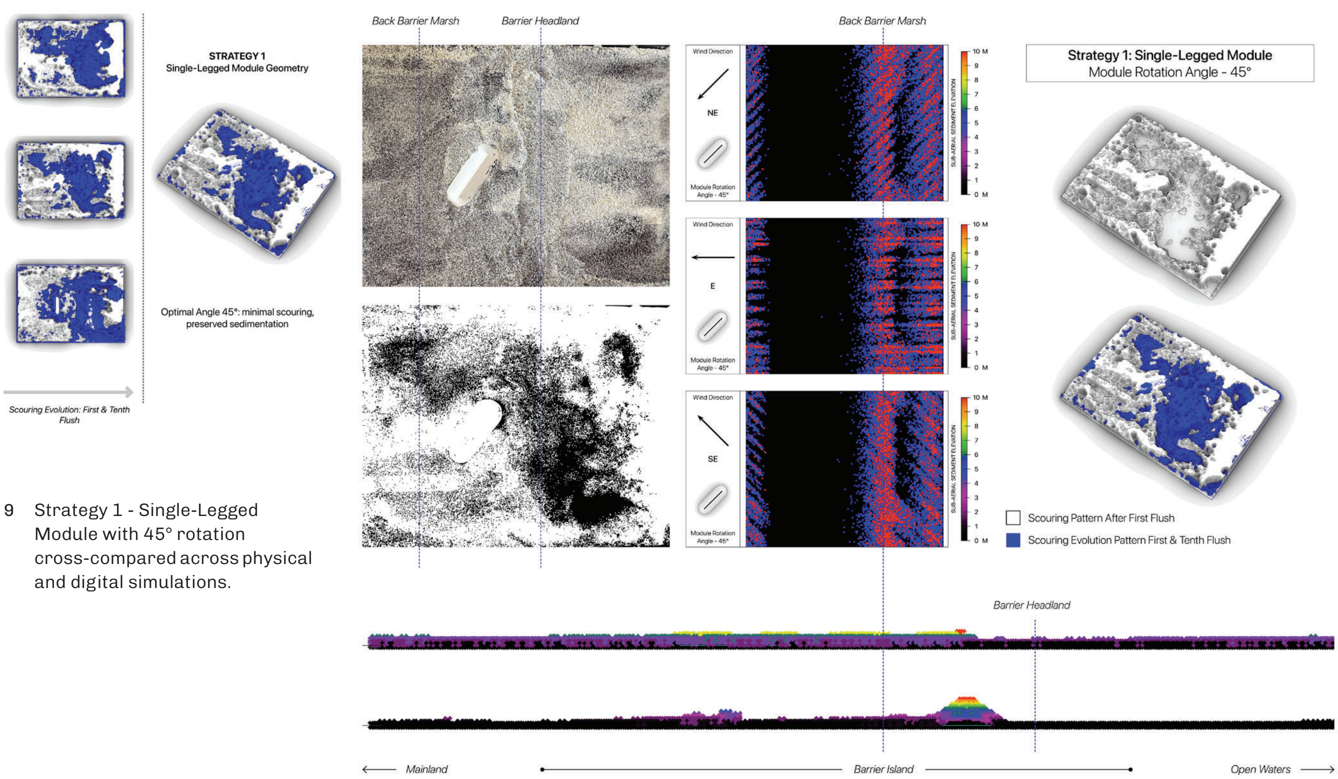
PLA 3D-printed dune modules—derived from Docofossor simulations—were tested in a 1:500 sand tub with a 1:1.5 vertical exaggeration. Modules (15 m max height, 50° slopes) were exposed to uphill water flushes toward the back-barrier marsh. Sediment displacement and scouring were tracked over 10 flushes with overhead imaging, and the slope was reset after each case for consistency.

Images from flushes 1 and 10 were traced and blurred to create depth-mapped texture maps, displaced 50 mm to model sediment dynamics. The resulting meshes were exported into Rhino, converted to surfaces, and contoured at 0.2 mm intervals to compare erosion and deposition



9 Strategy 1 - Single-Legged Module with 45° rotation cross-compared across physical and digital simulations.

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between initial and final states, synthesizing physical and digital simulations.

Phase Three: Comparative Evaluation of Test Cases

To evaluate dune performance under varied MICP-injection patterns, configurations are tested through digital simulations and physical sand-bed experiments. Effectiveness is measured by changes in subaerial elevation and maximum dune height, helping identify geometries most resilient to wind exposure. Image-based depth map analysis is then validated through sediment displacement, enabling direct cross-comparison between digital and physical outcomes.

Simulation outcomes were assessed by plotting the net percentage of subaerial sediment accretion against the maximum dune height achieved after 10 runs, enabling clear comparison of each rotation angle's effectiveness across the three wind directions. These results were then cross-referenced with volumetric erosion and deposition patterns observed in the physical sand-bed experiments.

In Strategy 1, physical tests showed that a 45° module orientation consistently reduced erosion on the dune's leeward side (Fig. 18) while 0° module orientation showed the most erosion. The 90° module orientation shows slight accumulation on the windward side of the module (Fig. 19).

Wind Direction	Module Rotation Angle	Sediment Above Baseline: Step 0	Sediment Above Baseline: Step 10	Dune Elevation Post-Ten Gusts (M)	Percentage of Net Accretion
NE	0°	2101	2424	10	13.33%
NE	45°	1935	2223	10	12.96%
NE	90°	1393	1582	10	11.95%
E	0°	2320	3581	7	35.21%
E	45°	2144	3126	7	31.41%
E	90°	1511	2225	10	32.09%
SE	0°	2068	2389	7	13.44%
SE	45°	1891	2142	7	11.72%
SE	90°	1393	1556	10	10.48%

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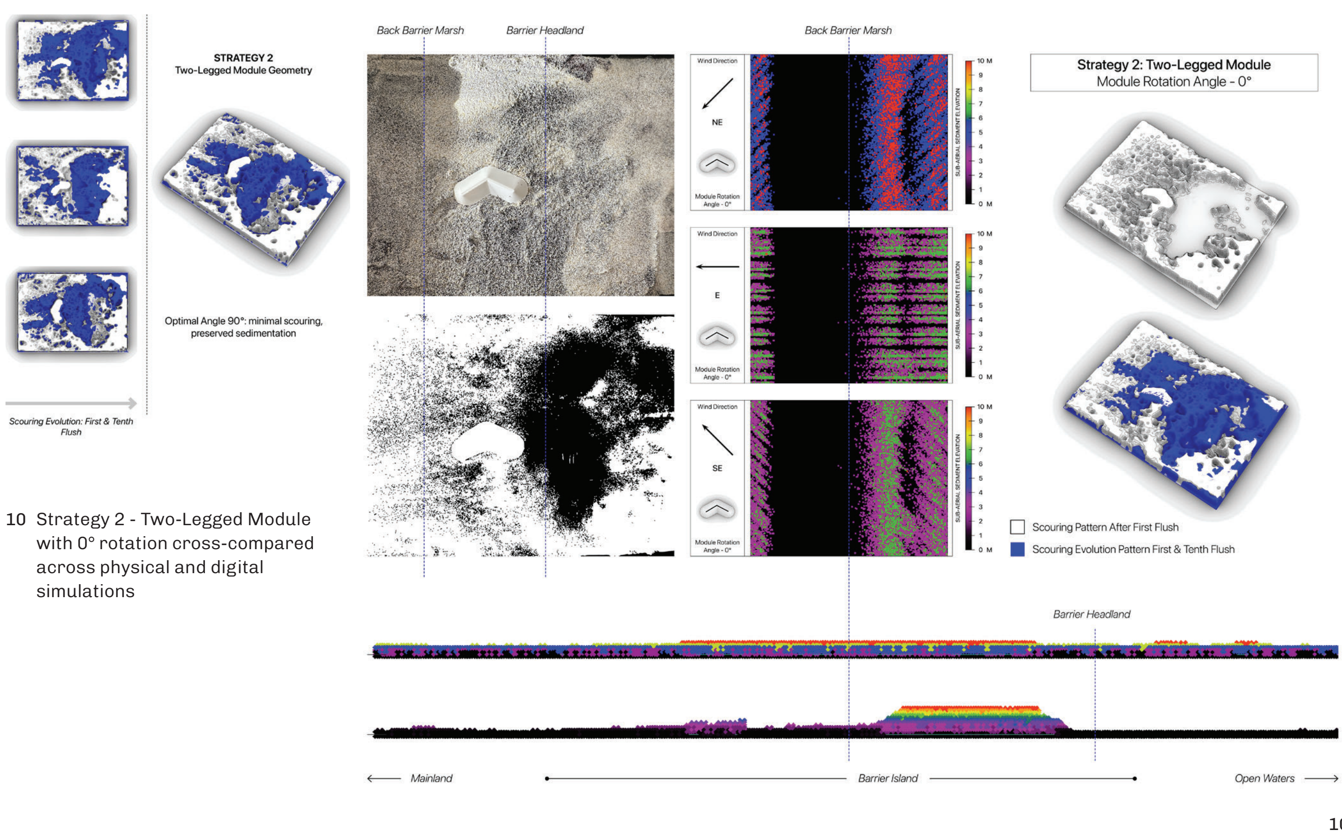
DuneWorm simulations for NE and SE winds indicate an optimal module angle of 45°, while for E winds, 45° shows the lowest performance, with 90° emerging as the best orientation (Fig. 20). The alignment between physical and digital results underscores the effectiveness of the 45° orientation across varying wind-driven wave conditions (Fig. 21).

In Strategy 2, physical tests showed that a 90° module orientation consistently minimized erosion from scouring on the dune's leeward side (Fig.10) while 0° module orientation showed the most erosion. The 45° orientation produced slight sand accumulation on the windward side of the module (Fig. 10). DuneWorm simulations for NE and SE winds show the 90° orientation with the lowest performance, while the 0° orientation achieves the highest net percentage of



10 Strategy 2 - Two-Legged Module with 0° rotation cross-compared across physical and digital simulations

subaerial sediment. For E wind, both 0° and 90° perform well, depending on dune elevation (Table). In this case, the DuneWorm simulation results take precedence over the physical tests, as the 0° module consistently performs best (Fig. 19).

For Strategy 3, physical tests indicated that a 90° orientation most effectively minimized leeward erosion (Fig.11) along with sediment accumulation on the windward side. The 45° orientation showed the most erosion from scouring. DuneWorm simulations indicate that under NE and SE wind directions, the 90° module orientation delivers the highest performance, whereas under E winds, the 45° degree orientation proves most effective (Table). Overall, the 90° configuration demonstrates strong potential for mitigating erosion across diverse wind conditions (Fig. 20).

Results Synthesis

After comparing the physical simulations with the digital terrain model trends, each strategy is evaluated across the NE, E, and SE wind directions. It is important to note that SE and E are the most prevalent winds, and therefore their results are given greater weight in the evaluation. Furthermore, sediment accumulation observed on the windward side during physical tests also informs the findings discussed in this section.

Wind Direction	Module Rotation Angle	Sediment Above Baseline: Step 0	Sediment Above Baseline: Step 10	Dune Elevation Post-Ten Gusts (M)	Percentage of Net Accretion
NE	0°	2312	2624	10	11.89%
NE	45°	2285	2439	10	6.31%
NE	90°	1898	2327	10	14.53%
E	0°	2561	3810	7	32.78%
E	45°	2544	3858	7	34.06%
E	90°	2291	3458	7	33.75%
SE	0°	2336	2628	10	11.11%
SE	45°	2269	2549	10	10.98%
SE	90°	2033	2410	10	15.64%

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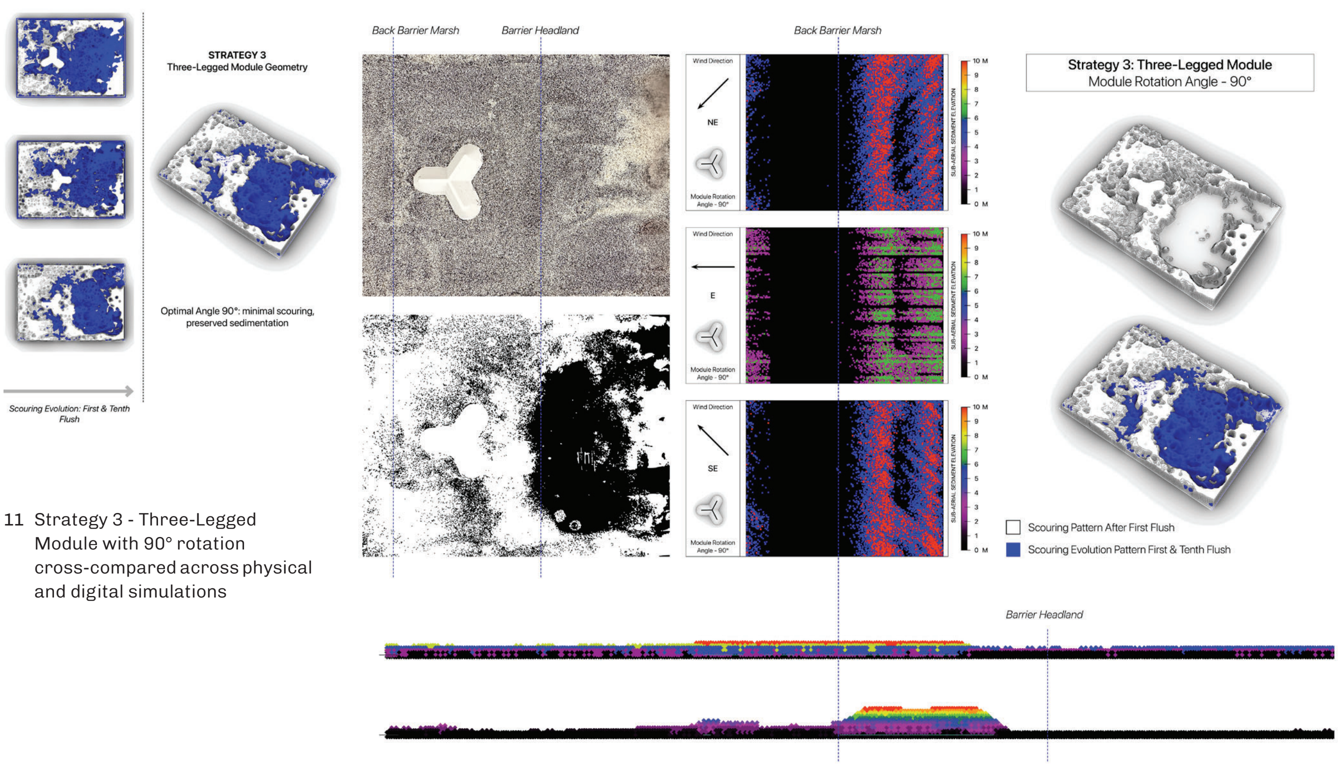
Across all strategies, module orientation strongly influenced dune resilience. The three-legged module (Strategy 3) at 90° consistently performed best under SE and NE winds, dispersing wave energy, enhancing sediment deposition, and reducing leeward erosion (Fig. 21). Its broader footprint improved stability across multiple directions. In contrast, Strategy 1 at 90° excelled under eastward winds, where its linear form acted as a barrier perpendicular to waves, supporting back-barrier sediment buildup (Fig. 23). Strategy 2 showed more flexibility, with 0° and 90° rotations adapting effectively to shifting wind directions (Fig. 22). Together, these results underscore that both geometry and orientation must be tuned to local wind regimes for effective barrier island restoration.



11 Strategy 3 - Three-Legged Module with 90° rotation cross-compared across physical and digital simulations

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CONCLUSION

In conclusion, this paper proposes an integrated computational framework for evaluating sedimentation dynamics and large-scale landscape behavior across scales. By embedding MICP-guided restoration strategies at the core, the study advances a regenerative approach to barrier island restoration—one that not only addresses immediate coastal erosion but also fosters long-term ecological resilience. Central to this framework is the emphasis on working with natural sediment redistribution processes, augmented through microbially induced calcium carbonate precipitation, a low-impact and scalable technique. This methodology reduces dependence on costly dredging and artificial nourishment, mitigating both economic burdens and ecological disturbance.

Equally important, the research underscores the role of strategic placement and morphology-informed terrain shaping in promoting natural dune formation and shoreline stability, while also preserving habitats for critical coastal species. Over time, such interventions can help barrier islands adaptively evolve under shifting climatic pressures, from sea level rise to increasingly severe storm events. Ultimately, this process-based, minimally invasive, "acupuncture-like" design ethos advances ecological regeneration by amplifying natural dynamics rather than imposing large-scale engineered solutions—offering a pathway toward resilient and sustainable coastal futures.

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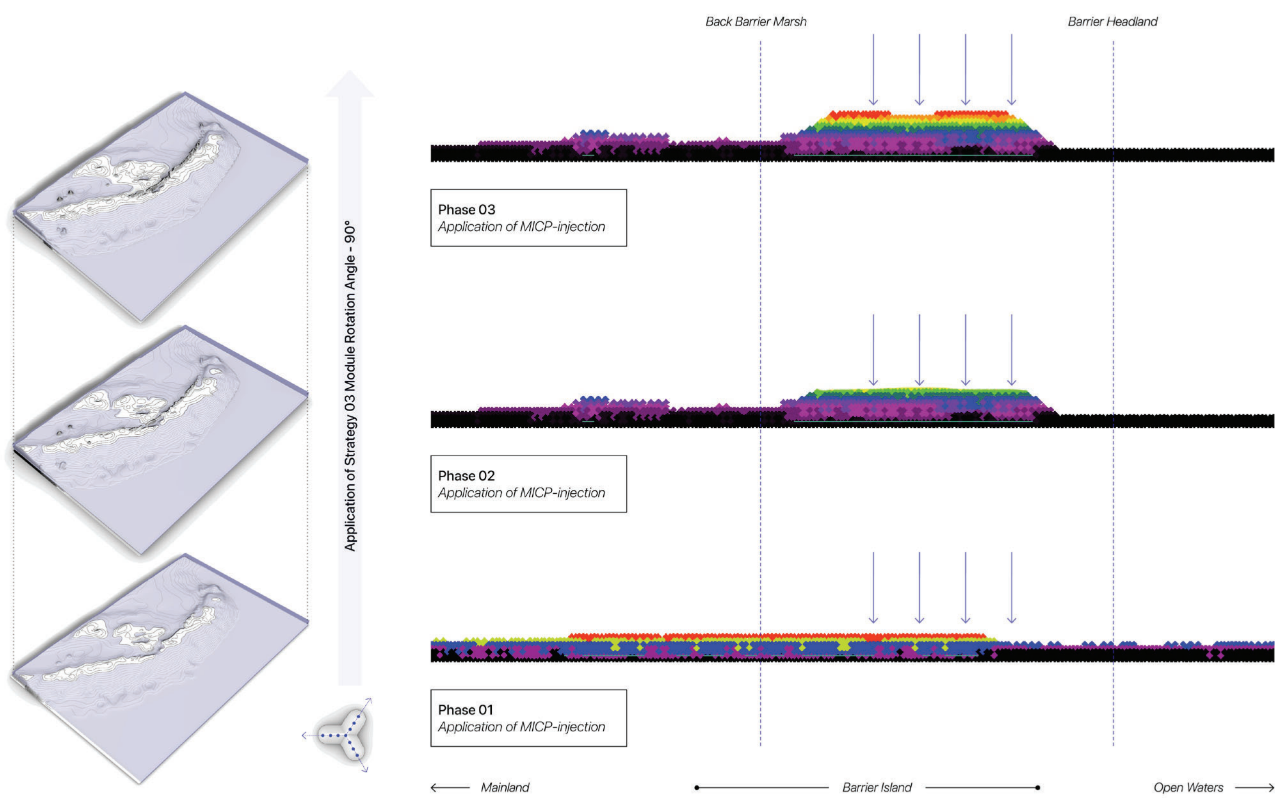
12 Projected impact of MICP application using the 90° three-legged module (Strategy 3), illustrating phased dune reconstruction and island rebuilding across three treatment stages over one year.



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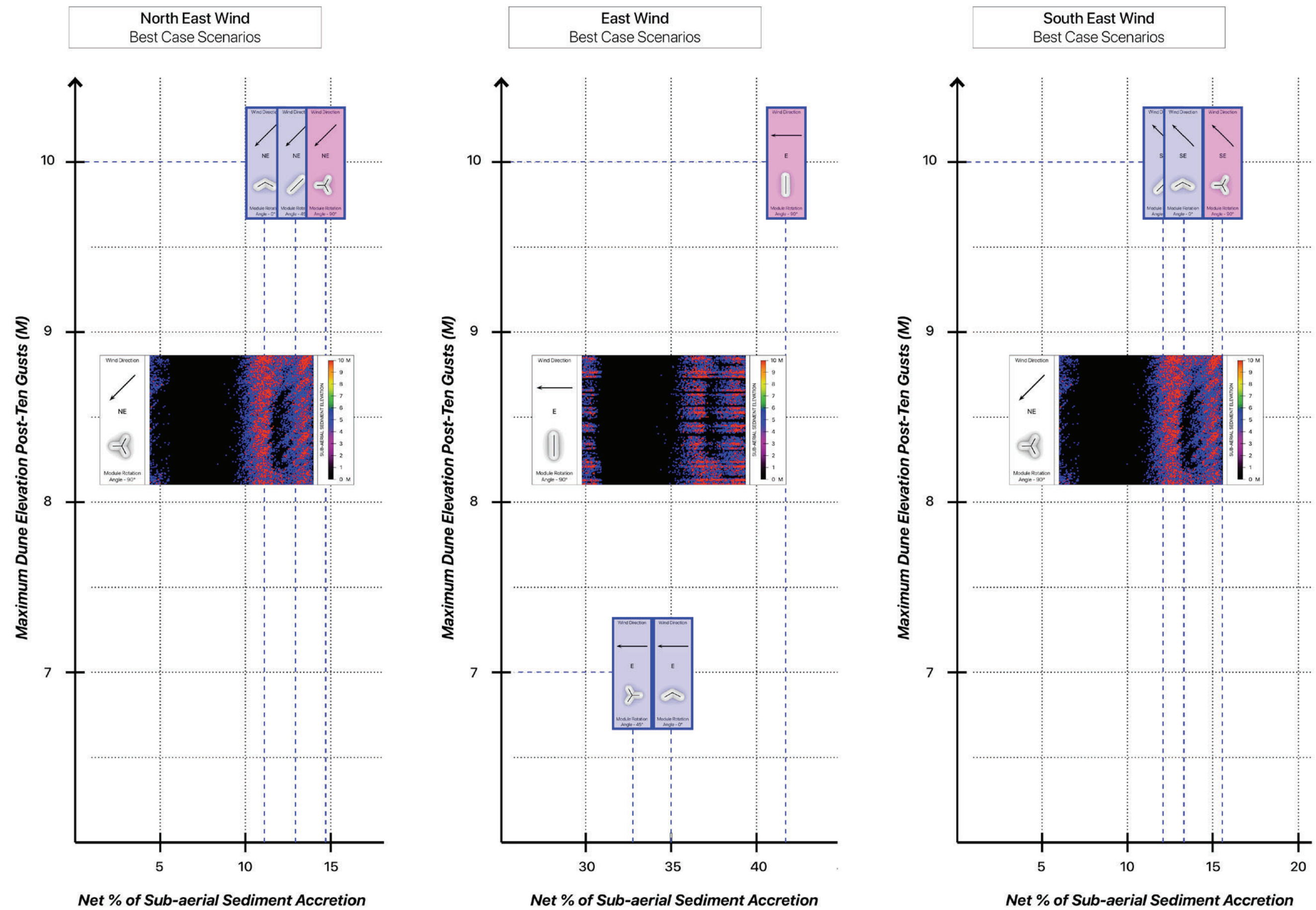

13 Best-performing module orientations by wind direction (NE, E, SE), based on net subaerial sediment accretion for each design iteration

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IMAGE CREDITS

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Khevna Modi holds a Masters' Degree in Sustainable Design from Carnegie Mellon School of Architecture. Her work explores planet-centered approaches that integrate ecological and carbon systems thinking to inform cross-scale resilience strategies. She is currently a Design and Wellness Fellow at Perkins Eastman, advancing carbon-conscious pathways to improve decision-making and deliver measurable outcomes. Her work bridges research and practice to advance climate-resilient, low-carbon design solutions.

Dana Cupkova is a Professor at Carnegie Mellon School of Architecture, Chair of the Sustainable Design graduate program, and Director of EPIPHYTE Lab. Dana's work is driven by a holistic vision of

the built environment, centered on the relationship between ecology and technology and the capacity of architecture to be ecologically vibrant. Seeking attunement with natural processes, her approach integrates evidence-based methods with creative design strategies, emphasizing the cross-scalar interconnectedness of architecture and landscape.

Christine Mondor is the founder and strategic principal of her design practice, evolveEA, and a Special Faculty member at Carnegie Mellon School of Architecture. In both her teaching and practice, Mondor builds interdisciplinary teams to explore sustainability and urban systems, with a focus on urban environments, ecology, and infrastructure. Her research centers on decentralized urban infrastructure and examines how water, energy, food, and mobility systems contribute to physical and cultural resiliency.