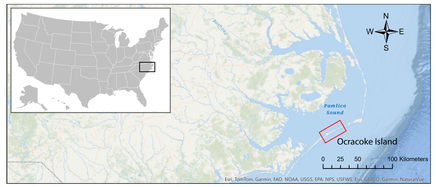
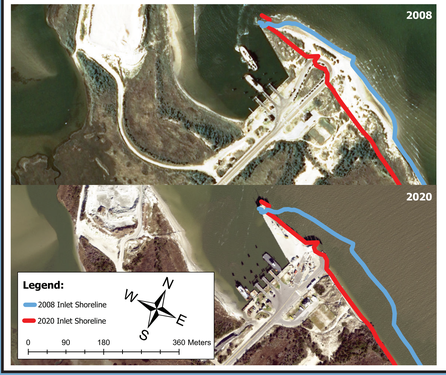
Simulating the Influence of Management Scenarios on Island Evolution, Ocracoke Island, North Carolina

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1. Motivation and Objectives





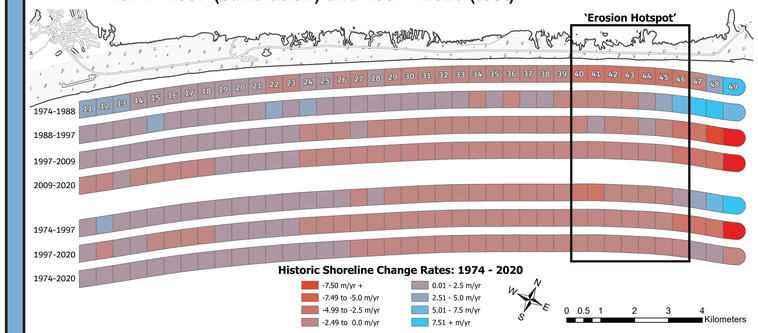
Ocracoke Island is located within the Outer Banks of North Carolina and is only accessible to the mainland by ferry.

Due to changing tidal inlet dynamics and historic shoreline erosion, maintaining transportation access is difficult.

To provide NPS and other stakeholders (local, state, federal) with information we are investigating the effects of three proposed management actions on the maintainance of a transportation corridor using the CoAStal-Community IAnDscape Evolution model (CASCADE; Anarde et al., 2024a,b).

2. Historic Change and Hindcast Results

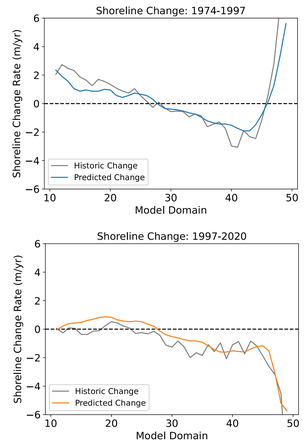
We divided hindcast periods into two intervals: 1974 - 1997 (calibration) and 1997 - 2020 (test)



Ocracoke has become increasingly erosive since 1974.

Changes in the northeastern tidal inlet on Ocracoke have resulted in alternating periods of significant erosion and accretion at the eastern end of the island.

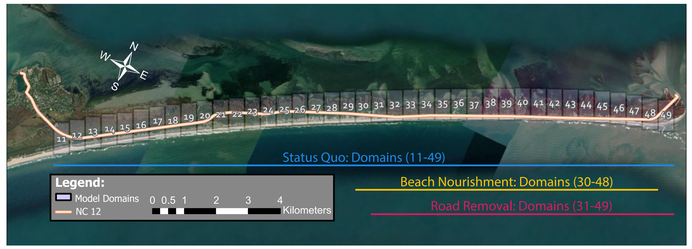
The 'Erosion Hotspot' is a major concern, and has remained largely erosive even during periods when changes in the inlet result in accretion.



CASCADE generates similar amounts of shoreline erosion for both periods.

Management actions (road relocation, dune building, sandbag construction) are consistent in timing and location with historic NCDOT actions.

3. Future Simulation Design



We modeled 36 different 126-year (2024-2150) scenarios varying:

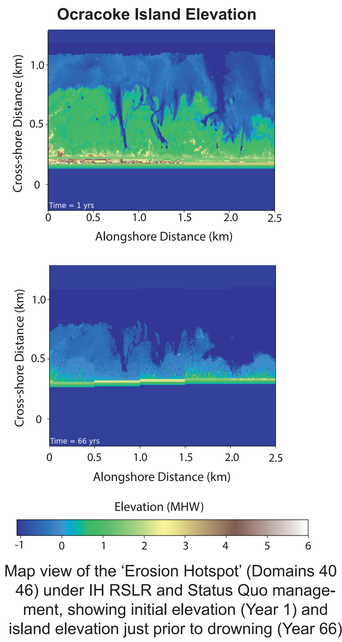
Relative Sea Level Rise by 2150
(Based on Sweet et al., 2022)
- Intermediate-Low (IL; 1.1 m)
- Intermediate (I; 2.1 m)
- Intermediate-High (IH; 2.7 m)

Management Actions
- Status Quo
- Beach Nourishment
- Road Removal

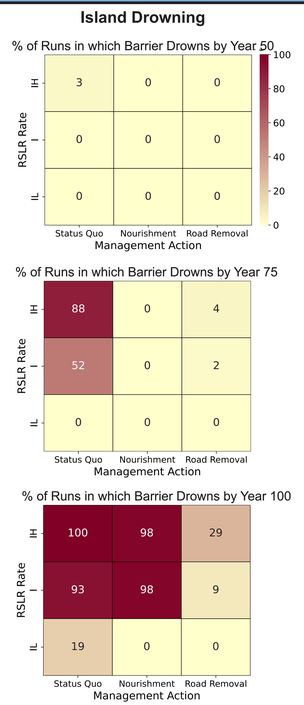
Inlet Dynamics
- Accretional
- Erosional

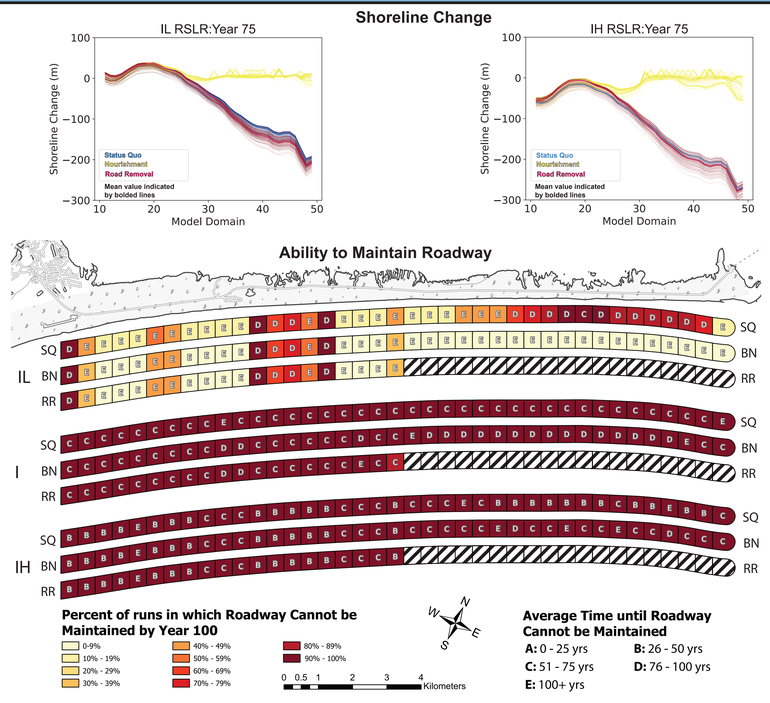
We ran each of the 36 combinations with 100 different random storm sequences to generate a range of possible future behavior.

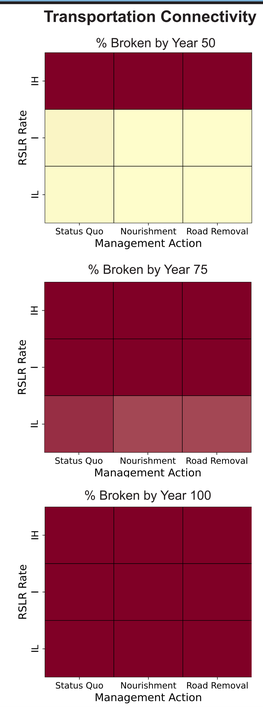
4. Future Simulations



Map view of the 'Erosion Hotspot' (Domains 40 - 46) under IH RSLR and Status Quo management, showing initial elevation (Year 1) and island elevation just prior to drowning (Year 66)







5. Conclusions and Future Work

1. Across all combinations of RSLR and management scenarios (except for low RSLR before 2075) transportation connectivity cannot be maintained.

2. Status Quo management leads to earlier drowning and at lower RSLR rates than in the Beach Nourishment and Road Removal Scenarios.

3. While the Beach Nourishment Scenario prevents shoreline recession at the 'Erosion Hotspot,' it leads to a high likelihood of island drowning by Year 100.

4. Road Removal leads to the largest amount of shoreline recession, effectively allowing Ocracoke to rollover, which reduces the probability of island drowning.

Next, we will:
Explore the effects of increased mean storm intensity (10% increase).

Refine simulations based on feedback from our agency partners (National Park Service, North Carolina Department of Transportation, Hyde County).

Host "deliberative dialogue events," designed to allow residents to engage with and discuss scenario outcomes, in Spring 2025.

6. Acknowledgments and References

We thank our project team members for their input on future simulation design and community engagement activities.This research was supported by the National Park Service under a Cooperative Agreement with the University of North Carolina at Chapel Hill and by the Preston Jones and Mary Elizabeth Frances Dean Martin Fellowship Fund within the Department of Earth, Marine, and Environmental Sciences. Disclosure: LJM and ABM are spouses.

Anarde, K. A., Moore, L. J., Murray, A. B., & Reeves, I. R. B. (2024a). The future of developed barrier systems: 1. Pathways toward uninhabitability, drowning, and rebound. Earth's Future, 12(4), 2023 003672. https://doi.org/10.1029/2023EF003672

Anarde, K. A., Moore, L. J., Murray, A. B., & Reeves, I. R. B. (2024b). The future of developed barrier systems: 2. Alongshore complexities and emergent climate change dynamics. Earth's Future, 12(4), 2023 004200. https://doi.org/10.1029/2023EF004200

How should we meet the challenges of access to Ocracoke?

Approach One: Current Road and Ferry System

This approach will continue the current management strategies of NC-Highway 12 on Ocracoke Island and the ferry routes that have been in place. NC-DOT to do its best to repair the roadway in a timely manner when the road is deemed impassable.

1A: NCDOT continues managing and repairing NC-Highway 12 as needed.	Repairing NC-12 is contingent on several factors: the ferry must be operational to allow NC-DOT personnel onto the island, funding must be available for repairs, road closure may be lengthy if repairs are delayed or time-consuming, and the frequency of needed repairs must be considered.
1B: Maintain and improve ferry routes and schedules.	South Dock is heavily impacted by erosion and flooding. If the terminal undergoes repairs, it could result in possible closures and higher costs. Adding additional ferry routes and time slots is dependent on funding and weather/ocean conditions.

Approach Two: Beach and Dune Management

This approach involves occasional beach nourishment along the oceanside, as the beach width erodes. This approach also involves maintaining the sandbags and improving dune structure near the road.

2A: Dunes will be repaired and built-up when needed.	Dune management could be costly if repairs/construction is needed multiple times a year or after major storms/flood events. Preventing overwash events makes the road and island interior lower and more vulnerable to storms and soundside flooding
2B: Beach Nourishment will be performed on the island every 3-5 years.	Storm frequency and coastal erosion could require beach nourishment more often which can result in higher costs. Reductions in overwash sediment makes the road and island interior lower and more vulnerable to storms and soundside flooding.

Approach Three: Roadway Alternatives

This approach involves no longer maintaining NC-Highway 12 from Ocracoke Village to South Dock. Alternatives could include additional ferry service to the Village, a causeway or a bridge.

3A: No longer maintain NC-Highway 12 from the Pony Pens to South Dock and allow the roadway corridor to undergo natural processes without human interference.	No longer maintaining the road would require alternative means for getting to/from the island. The island would migrate at a faster rate in locations where the highway recently was, but would likely stay above sea level for longer, compared to the other two approaches.
3B: Build a bridge from Hatteras to South Dock or a suspended roadway from South Dock to Ocracoke Village.	Building an expansive jug-handle bridge or a new elevated roadway would be costly and require a high degree of engineering and funding. Bridges also experience closures during high winds and major storms which would impact traffic and transportation.

Conclusions from Simulations

Approach One: Current Road and Ferry System

Model runs resulted in:

- **Narrowing of the island** over time. This occurs due to bayside inundation and shoreline erosion.
- The frequency of **flooding and overwash will increase** steadily.
- **Within 51-75 years**, the entire length of the road will likely be continuously **submerged.**

Approach Two: Beach and Dune Management

Model runs resulted in:

- **Narrowing of the island** over time. This occurs due to inundation of the island on the bayside while the ocean shoreline remains stable as long as nourishment keeps up with erosion.
- The frequency of **flooding and overwash will increase** steadily.
- **Within 51-75 years**, much of NC Hwy 12 will likely be continuously **submerged**.

Approach Three: Roadway Alternatives

Model runs resulted in:

- **Less island narrowing** than the other approaches and landward island migration.
- The **bayside shoreline remains more stable** or grows landward, while the **ocean shoreline erodes.**
- **Within 51-75 years**, the roadway between Ocracoke Village and the Pony Pens becomes continuously **submerged**.

Dialogue Goals & Format

The goal of this "deliberative dialogue" event is to share information with and seek the opinions of Ocracoke residents, regarding possible management approaches for NC-12, affecting access to Ocracoke Village.

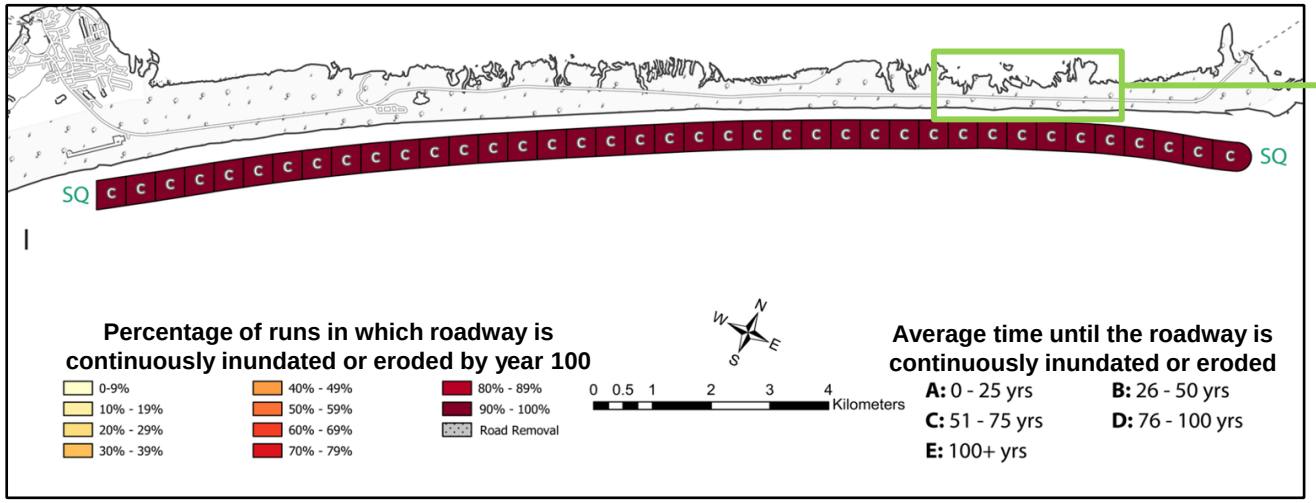
1. **Welcome (about 10 min)**
2. **Deliberations in small groups (about 65 minutes)**
3. **Expert Panel (about 10 min)**
4. **Conclusion & Participant questionnaire (about 5 min)**



[Image Credit: NPS]

Notes

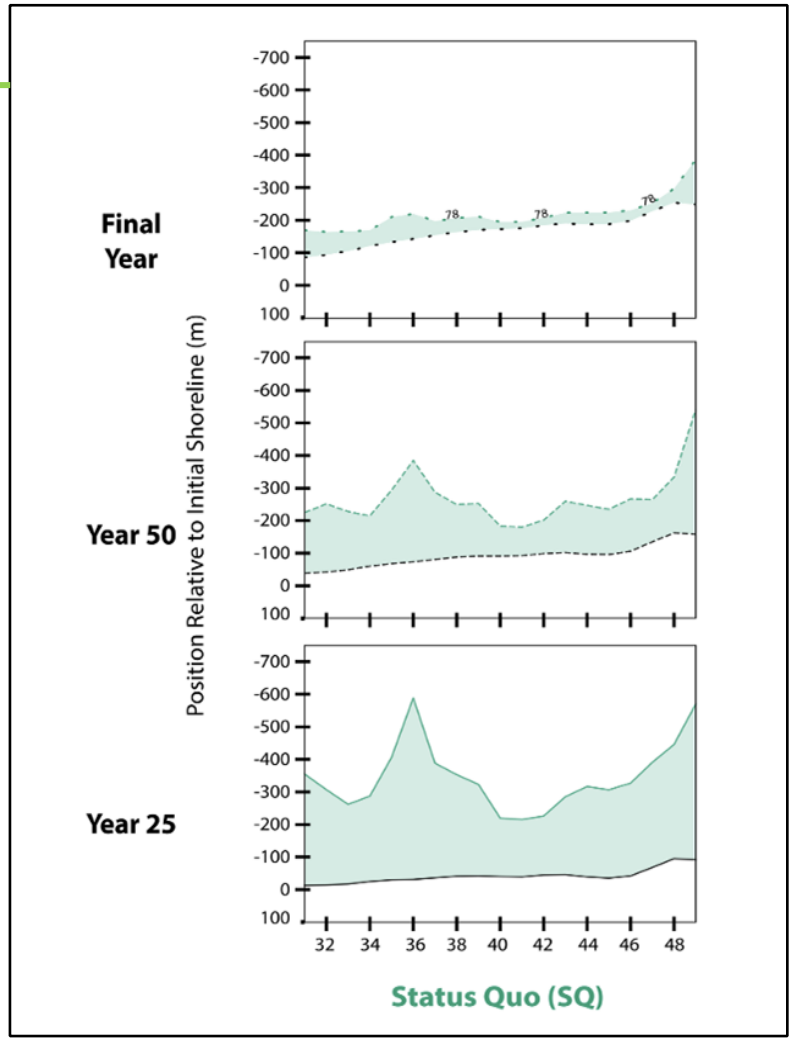
Approach One: Current Road and Ferry System



The diagram above shows a top-down view of the entire island. In this scenario, the road is likely to be continuously submerged along all domains within 51-75 years.

The diagram on the right is a top-down view of the island from model domains 32-48 (known as the 'erosion hot spot') at 25 years, 50 years, and 78 years. The shaded green area shows all land above sea level (at still water), with 0 indicating the current ocean shoreline.

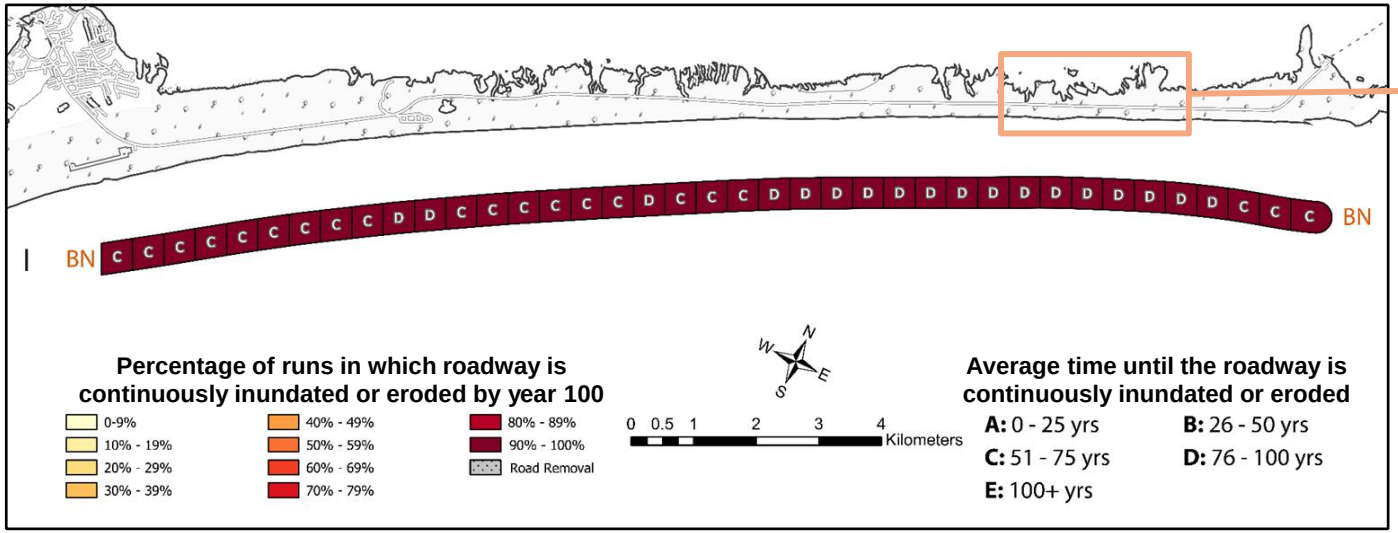
In this scenario, management reduces sediment transport to the island's interior, leading to island narrowing from a combination of bayside inundation and ocean shoreline erosion in years 0 -77. On average, this area drowns at model-year 78.



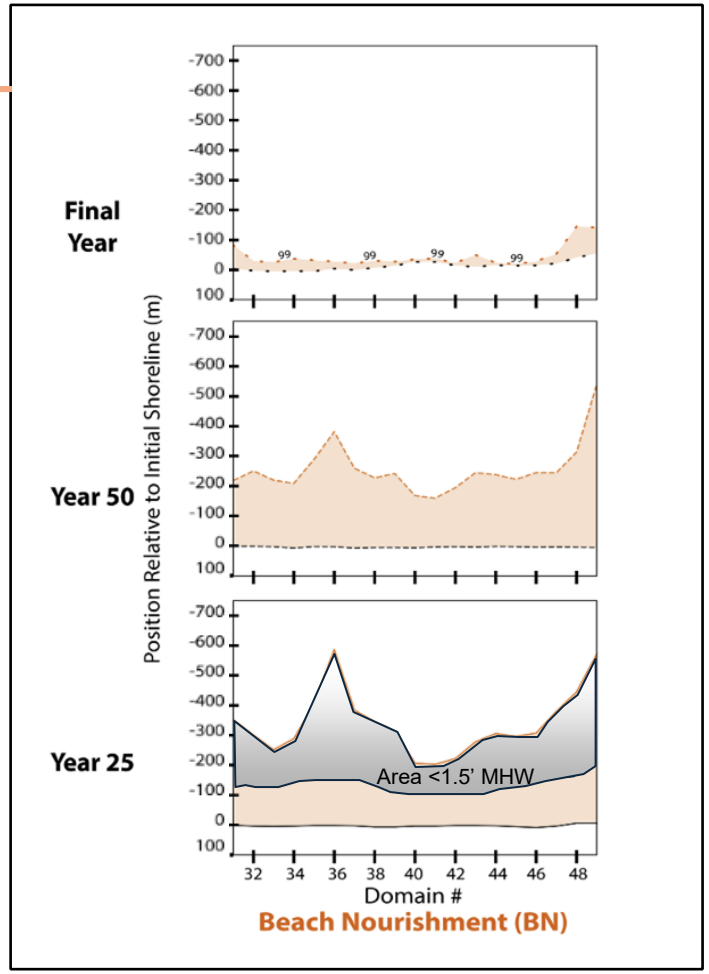
Franklin et al., in preparation for submission *to Earth's Future*

Model results indicate: Narrowing of the island over time due to bayside inundation and shoreline erosion. Flooding and overwash frequency will increase over time. The entire length of NC-Hwy 12 will be continuously submerged by ~51-75 years.

Approach Two: Beach and Dune Management



The diagram above shows a top-down view of the entire island. In this scenario, the road is likely continuously submerged within 51-75 years along the southern and central portions of the island and near the inlet. Continuous inundation is likely delayed to within 76-100 years near the Pony Pens and in the erosion hotspot.



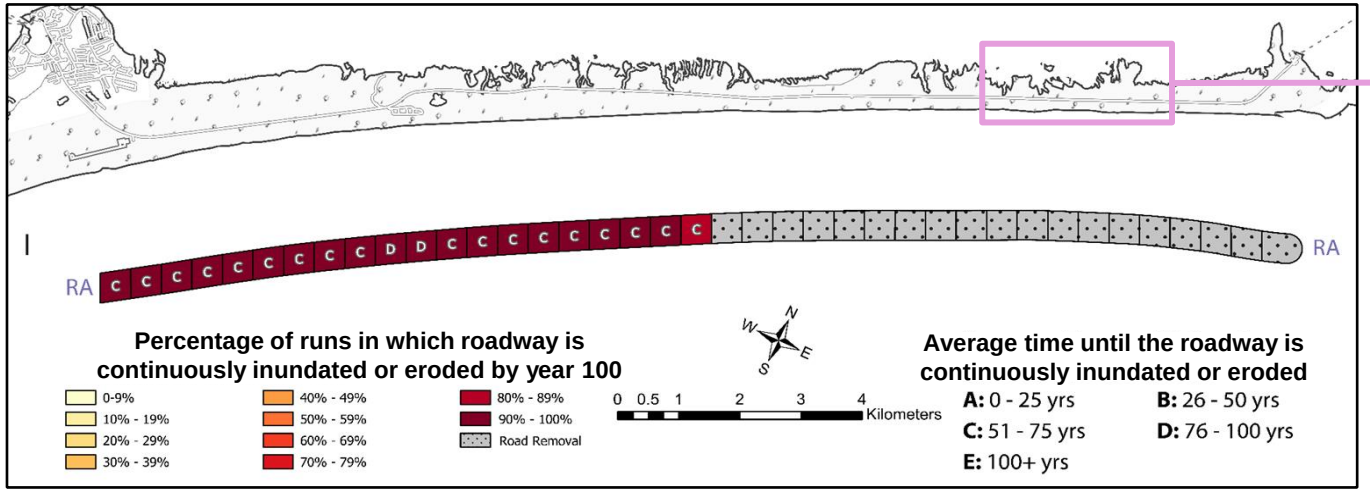
The diagram to the right shows a top-down view of the island from domains 32-48 (known as the 'erosion hot spot') at 25 years, 50 years, and 99 years. The shaded orange area shows all land above sea level (at still water), with 0 indicating the current ocean shoreline.

In this scenario, on average, the island drowns at year 99. If nourishment occurs frequently enough, it mitigates ocean shoreline erosion. This, along with dune construction, reduces sediment transport to the island interior leading to island narrowing from bayside inundation.

Franklin et al., in preparation for submission *to Earth's Future*

Model results indicate: Narrowing of the island over time due to inundation on the bayside while the ocean shoreline remains stable (as long as nourishment is frequent enough). The frequency of flooding and overwash will increase over time. Much of NC-Hwy 12 will be continuously submerged within ~51-75 years, with the remaining roadway submerged by ~76-100 years.

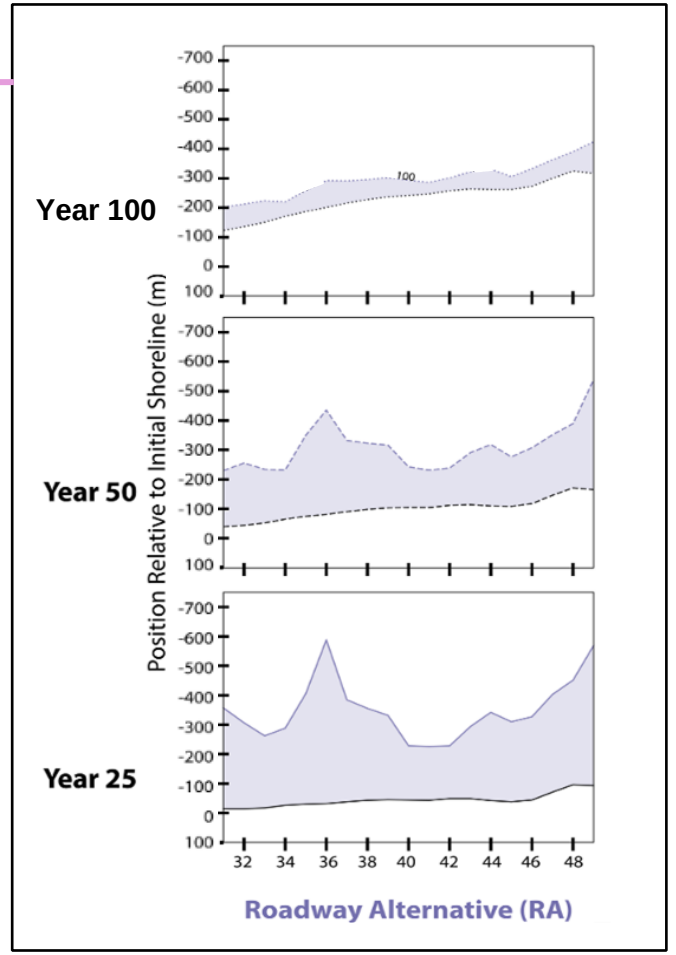
Approach Three: Roadway Alternatives



The diagram above shows a top-down view of the entire island. In this scenario, like the others, the road is likely continuously submerged within 51-75 years along the stretch from the Pony Pens to the Village.
[Note: Because the roadway isn't managed where the gray boxes are shown, there are no roadway results to report for the northern portion of the island.]

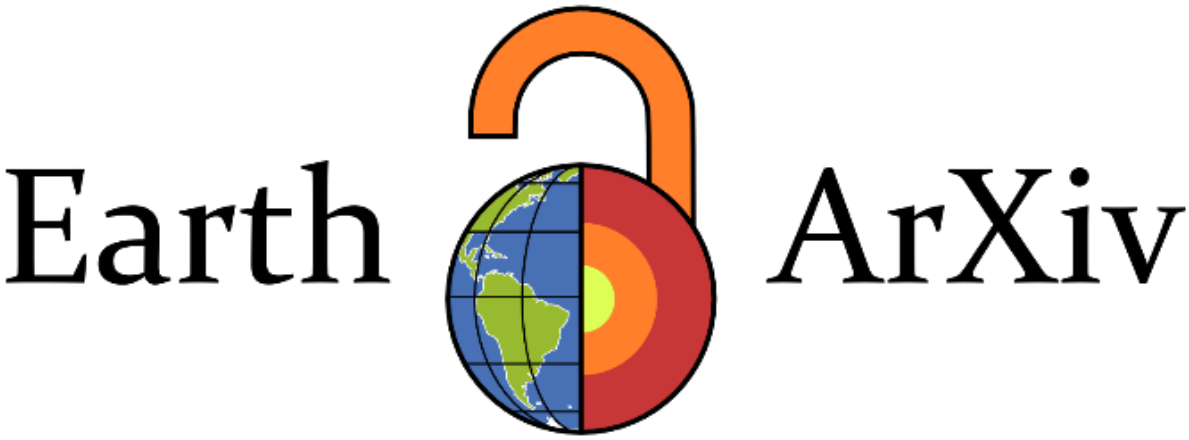
The diagram to the right shows a top-down view of the island from domains 32-48 (known as the 'erosion hot spot') at 25 years, 50 years, and 100 years. The shaded purple area shows shows all land above sea level (at still water), with 0 indicating the current ocean shoreline.

In this scenario, the island moves landward instead of drowning. As it moves, the island becomes narrower due to ocean shoreline erosion and minor bayside inundation. There is greater sediment transport to the island interior compared to approaches 1 and 2, leading to less bayside inundation and a lack of drowning.



Franklin et al., in preparation for submission *to Earth's Future*

Model results indicate: Less island narrowing than the other approaches and landward island migration. The bayside shoreline is maintained by overwash as the ocean shoreline erodes. Flooding of the roadway from the Pony Pens to Ocracoke will increase over time. The road from the Ocracoke Village to the pony Pens will be continuously submerged within 51-75 years.



Peer review status:

This is a non-peer-reviewed preprint submitted to EarthArXiv. This paper has been submitted to *Earth's Future* and is currently in review. Subsequent versions of this manuscript may have slightly different content. If accepted, the final version of this manuscript will be available via the "Peer-reviewed Publication DOI" link on the right-hand side of this page. Please feel free to contact the corresponding author (Moore). We welcome feedback.

Multi-decadal Barrier Island Fate Varies as a Function of Management Strategy

Benton Franklin, Laura J. Moore, Katherine A. Anarde, A. Brad Murray, K.C. Busch, D. Reide Corbett, Michael J. Flynn, Meaghan E. Johnson, David E. Hallac, and Roya Sahraei

Key Points

1. Calibrating CASCADE for a developed barrier, adding sandbags and inlets, yields broadly applicable insights and supports decision making
2. Different management strategies yield different effects on island width, position, persistence and ability to host a land-based roadway
3. Increased sea-level rise and inlet-induced erosion exacerbate management-induced washover reduction, hastening fragmentation and drowning

Abstract

Barrier islands are highly dynamic components of sandy coastlines, making up 10% of coastlines globally. Barriers provide recreational opportunities, protect mainland communities from storms, support tourism, and provide ecologically important habitat. Using a spatially explicit barrier island model, CASCADE, calibrated to represent the historical dynamics of Ocracoke, a barrier island in the Cape Hatteras National Seashore in the North Carolina Outer Banks facing severe transportation challenges and divergent stakeholder missions and goals, we investigated how different strategies for maintaining a transportation corridor can affect future barrier island morphology and evolution. Compared to natural conditions, model runs in which roadways are maintained on land using artificial dune construction, sandbag emplacement, washover removal, and beach nourishment result in decreased washover deposition in the island interior leading to increased risk of island drowning along some portions of the barrier, potentially within 50 – 100 model years. The effects of decreases in washover deposition become increasingly severe under higher rates of relative sea-level rise, leading to more rapid island drowning from backbarrier inundation, precluding maintenance of a land-based transportation corridor. Model

results also indicate that preemptively halting land-based roadway maintenance allows natural processes to resume, leading to rollover and longer-term island persistence. Consistent with observations and modeling from previous studies, our results demonstrate quantifiable differences in island morphology and evolution based on different management practices undertaken to protect transportation corridors on barrier islands. These outcomes highlight the challenges and tradeoffs associated with addressing competing priorities on barrier islands managed for divergent interests.

Plain Language Summary:

Common features of many coastal areas, barrier islands change shape and location over time in response to natural processes such as sea-level rise and storms. We used a barrier island model (CASCADE) to explore how three common strategies used to maintain roadways on barrier islands might alter the 25-year to 100-year evolution of a North Carolina barrier island facing transportation access challenges. Model experiments show quantifiable differences in island shape, size and position depending on the management strategy used to maintain the island roadway. These differences arise because actions like dune construction, sandbag emplacement, and removal of sand from roads disrupt natural overwash processes. Our results highlight how management actions designed to maintain current transportation corridors on barrier islands can hasten the loss of island area and accelerate partial island drowning.

1. Introduction

Barrier islands are highly dynamic coastal landforms that comprise ~10% of global coastlines (Stutz & Pilkey, 2011), providing numerous societal, economic, and ecological benefits. Barriers islands evolve over short time scales in response to storm events (Dolan & Godfrey, 1973; Leatherman, 1979; Morton & Sallenger Jr, 2003; Timmons et al., 2010), relative sea-level rise (RSLR; Ashton & Lorenzo-Trueba, 2018; Leatherman, 1983; Mariotti & Hein, 2022; Moore et al., 2010), tidal-inlet dynamics (Fenster & Dolan, 1996; Fitzgerald et al., 1984; Inman & Dolan, 1989; Leatherman, 1979), and changes in sediment supply (Cipriani & Stone, 2001; Otvos &

Carter, 2013; Robbins et al., 2022; Timmons et al., 2010). Where sea level is rising and/or sediment supply is limiting (e.g. FitzGerald et al., 2008; Moore et al., 2010), islands tend to move landward over time, aided by overwash which occurs during storms when water levels exceed dune crest elevations (Sallenger Jr, 2000). During overwash events, sand is transported from the front of an island to the interior or beyond. Over long timescales, this deposition of sand maintains island width and elevation relative to sea level.

Because storm flooding and overwash processes leading to washover deposition can be damaging to infrastructure in the short term and lead to roadway impacts and temporary closures, these effects are mitigated on developed barrier islands using various management actions (Flynn & Hallac, 2021; Flynn et al., 2023). For example, a common practice is to protect ocean-adjacent roadways by constructing artificial dunes (Sciaudone et al., 2016), or to rebuild dunes after erosion by storms (Elko et al., 2016; Nordstrom & Jackson, 1995). Because roadways must be kept free of sand to function as transportation corridors, whenever washover is deposited on a roadway during storms or high-water events, it must be removed. The removed sand is commonly placed back on the beach or used in dune construction (Douglass & Webb, 2020; Velasquez-Montoya et al., 2021).

Where it is impractical to rebuild eroded dunes because of chronic shoreline erosion, sandbags may be used in accordance with applicable rules, regulations, and permitting processes to provide temporary erosion-resistant protection to roadways. Beach nourishment is another common management practice aimed at mitigating shoreline erosion (Elko et al., 2021). During nourishment events, sand is added to the beach near the shoreline, resulting in immediate seaward beach extension. Although artificial dune construction, washover removal, sandbags, and beach nourishment provide temporary protection, roadways that are chronically flooded,

damaged, or closed due to proximity to the ocean are sometimes relocated landward to reduce the risk of ocean-side storm impacts (Douglass & Webb, 2020). Barrier island communities commonly use these management approaches in various combinations, according to their specific needs, desires, and resources.

Recent research (Anarde et al., 2024a; 2024b) presenting and using the barrier island model CASCADE (CoAStal Community-lAnDscape Evolution model) demonstrates the effects of roadway management actions on the long-term geomorphic evolution of developed barrier islands. Management actions such as artificial dune construction, beach nourishment, and washover removal reduce overwash delivery to the island interior, increasing the likelihood of barrier drowning. Once management ceases, modeled islands either drown or rebound depending on the initial island topography and the timing and intensity of storm events relative to dune elevation at the times of those storms (Anarde et al., 2024a). The model experiments also suggest that the preemptive, partial abandonment of roadways (accompanied by cessation of management actions) results in greater amounts of washover, creating a higher and wider barrier island (Anarde et al., 2024b).

Here, we build upon this previous work by adding new model functionality, developing the model to represent a specific barrier island affected by inlet processes and assessing the effects of different combinations of roadway management practices actively under consideration and for a range of plausible climate change scenarios. To ground our investigation in a real-world landscape and management scenarios, our work features a partnership between researchers and staff at the Cape Hatteras National Seashore (hereafter referred to as the Seashore) and the Village of Ocracoke (hereafter referred to as the Village), located within the Outer Banks of North Carolina (Figure 1). Ocracoke is an ideal case study because the Seashore and residents of

the Village face extreme difficulty maintaining a transportation corridor along the northeastern section of the island, a challenge soon to become more prevalent in similar barrier island settings. To advance understanding of coupled human-natural barrier dynamics and, at the same time, enhance the usefulness of our findings to communities in North Carolina (NC), we our project included representatives from Hyde County, North Carolina Department of Transportation (NCDOT) Ferry Division, NCDOT Highway Division, the NCDOT contractor HDR, and the local utility company Tideland EMC.



Figure 1: Ocracoke Island is located in North Carolina, U.S.A. and North Carolina Highway 12 (NC 12) is the primary transportation corridor. The majority of land between Oregon Inlet and Ocracoke Inlet is part of the Cape Hatteras National Seashore.

Prior to carrying out future model runs, we conducted a series of hindcast runs to calibrate and then test CASCADE's ability to replicate historic changes. After confirming model skill, we used our calibrated model to investigate the future geomorphic effects of three different combinations of roadway management strategies under three different projected RSLR rates and for two different inlet conditions. Combining these conditions yields 18 unique scenarios, which we selected in collaboration with the project team, to maximize the regional utility of the broadly generalizable insights gained from this work.

2. Site Setting

The NC Outer Banks are a well-studied barrier island chain extending ~ 320 km from the NC-Virginia border to the western edge of Bogue Banks (Moslow & Heron, 1994). Shallow sounds 3 –30 km wide separate the islands from the mainland. Ocracoke, located southwest of Cape Hatteras and northeast of Cape Lookout, is separated from Hatteras Island by Hatteras Inlet and from Portsmouth Island by Ocracoke Inlet (Figure 1). Processes associated with the highly dynamic Hatteras Inlet generate variable shoreline change patterns in its vicinity, with substantial shoreline accretion occurring near the inlet between 1974–1997 and shoreline erosion near the inlet between 1997–2017 (Figure S1). Considering long-term island-wide shoreline change patterns, between 1949 and 2006, the oceanside shoreline eroded an average of ~0.5m/yr while the bayside shoreline accreted at ~ 0.1m/yr, leading to island narrowing (Conery et al., 2018). Most recently between 2009 and 2020, the oceanside shoreline eroded at an average of ~1.37 m/yr between the Village and Hatteras Inlet (this study).

The Village, located on the southern end of the island, is home to ~800 people (U.S. Census, 2020). The remainder of the island is part of the Seashore. Ocracoke is only accessible via ferry or private plane, making transportation to and from the island challenging and, at times,

unreliable. North Carolina Highway 12 (NC 12) connects the Village (where one ferry terminal is located) with the northern end of Ocracoke where a second ferry terminal is located. The NCDOT maintains NC 12 on Ocracoke using a combination of dune construction, washover removal from the roadway, return of washover to the dune line, sandbag emplacement, and (historical) roadway relocation. Although NC 12 is a critical link connecting the two ferry terminals, its frequent closure because of flooding associated with storms, high tides and even northeast winds, poses a major challenge for residents, park visitors and park staff. The most vulnerable section of this roadway (labeled 'Erosion Hotspot' in Figure 2, and hereafter referred to as the erosion hotspot) is one of seven designated erosion hotspots in the Outer Banks (Highway 12 Task Force Subcommittee, 2023).



Figure 2: Map of Ocracoke Island, divided into model domains and indicating where the Status Quo (Domains 1 – 39), Beach Nourishment (Domains 20 – 39) and Roadway Alternative (Domains 21 – 39) management strategies are implemented in CASCADE.

3. CASCADE

CASCADE (Anarde et al., 2024a, 2024b) is a spatially explicit barrier island modeling framework that couples the barrier island model Barrier3D (B3D; Reeves et al., 2021) with the BarrieR Inlet Environment (BRIE) model (Nienhuis & Lorenzo-Trueba, 2019a, 2019b) as well

as modules that simulate barrier island management actions. B3D is a cellular grid model, which uses a series of 10 m x10 m cells to represent island position and elevation within a domain that measures 500 m in the alongshore dimension by 1000 m in the cross-shore dimension. CASCADE uses B3D to model the effects of RSLR, dune dynamics, storms, and overwash processes. Within CASCADE, overwash occurs during storms when water levels exceed the dune elevation (as in Sallenger 2000). Water flow and sediment transport then occur in the model according to differences in elevation between cells and following the flow routing formulations of Murray & Paola (1994; 1997). To represent alongshore sediment transport processes, CASCADE connects multiple B3D model domains using BRIE. Within CASCADE, BRIE resolves alongshore sediment transport based on shoreline diffusion using formulations from Ashton & Murray (2006a).

CASCADE runs for the specified time period or until all interior (non-dune) cells within any one B3D model domain fall below 0 m elevation, a condition we refer to as the 'initiation of island drowning,' at which point the model run ends. When CASCADE stops running due to the initiation of drowning, this implies only that at least one entire domain is persistently submerged and therefore unusable as a land-based transportation corridor, or for habitation or recreation; importantly, adjacent domains may still be above 0 m mean high water (MHW). Because runs end upon the initiation of island downing, CASCADE does not currently model continued degradation or potential recovery after the initiation of drowning.

3.1 Human Dynamic Modules

To explore the effect of roadway management strategies associated with the maintenance of roads like NC 12, we utilized CASCADE's roadway and community management modules, which include artificial dune construction, washover removal, roadway relocation and beach

nourishment. Within CASCADE, artificial dune construction occurs when dune elevation falls below a minimum dune elevation threshold relative to the roadway elevation, at which time dunes are "rebuilt" to a specified design elevation, again relative to the roadway. This combination of model actions ensures that dunes provide consistent protection to the roadway. Following storm events, CASCADE removes any washover deposited on roadway cells and places it on nearby dune cells. CASCADE also relocates roadways landward when the current roadway location is threatened by shoreline erosion, when the roadway elevation is below 0 m (MHW), or when a user-specified number of cells behind (or in front of) the roadway fall below 0 m (MHW) in elevation. If there is no dry land in the barrier interior to relocate the roadway to, the roadway is abandoned. When the roadway is abandoned in any one 500 m wide model domain, the roadway corridor becomes fragmented, representing a gap in (land-based) transportation connectivity among different sections of the island, hereafter referred to as 'roadway-corridor fragmentation.' CASCADE represents the effects of beach nourishment by adding a user-specified volume of sand to the upper shoreface, resulting in seaward shoreline growth.

Accurately representing management practices in our study area required us to add a new formulation to CASCADE to represent the emplacement of sandbags and their effects. Within CASCADE, sandbag emplacement occurs for individual dune cells whenever the roadway is within 10 m of the dune line and dune elevation falls below a user-specified threshold. When these conditions are met, CASCADE applies additional rules to each dune cell lower than the threshold elevation: dunes are rebuilt to a user-specified elevation and prevented from being eroded or scarped by storms, thereby representing a hardened structure (see Section 4.1 for parameter values used in this study).

3.2 Customizing CASCADE for Ocracoke

Focusing on the 19-km (~12-mile) stretch from the northern ferry terminal to the Village, we represent Ocracoke with 39 alongshore-connected, 500 m x 1000 m model domains (Figure 2). As described below, accurately representing Ocracoke within CASCADE required creating representative initial topography, ensuring domain positions reflect representative alongshore island shape, generating representative RSLR rates and storm sequences, and approximating the background shoreline change effects of the northern tidal inlet.

We generated initial topography for each domain by extracting elevation values from LiDaR, collected in 2017 LiDaR survey (Office for Coastal Management, 2023b) resampled to 10 m x 10 m resolution. After resampling, we converted elevation from the North American Vertical Datum 1988 (NAVD88) to the CASCADE vertical reference frame (Oceanside MHW; -0.26 m NAVD88, from Morton & Miller, 2005). Because CASCADE uses simplified beach dynamics, we measured domain cross-shore position relative to the foredune toe, identified as the intersection between the beach and the continuous foredune line that had a sharp color contrast visible, using aerial photographs (1974 and 1997 for hindcasts; 2017 for future runs). We calculated the average dune toe position for each domain by measuring the distance between the dune toe and the fixed offshore baseline for transects spaced at 100 m intervals alongshore. Because CASCADE uses continuous (periodic) model boundary conditions, we included 30 buffer domains between Domains 39 and 1 to prevent changes in Domain 1's cross-shore position from influencing Domain #39 and vice-versa. To ensure the proper location of NC 12, we digitized NC 12's centerline location from aerial photographs for hindcasts and we obtained current centerline from a NCDOT highway web layer (NC Department of Information Technology-Transportation, GIS Unit, 2025) for future runs.

3.3 Accounting for Climate Changes

Relative Sea-Level Rise Rates

We created three RSLR curves for future runs analogous to the Intermediate-low (IL), Intermediate (I), and Intermediate-high (IH) sea-level scenarios for the southeastern United States based on the latest NOAA technical sea-level rise report (Sweet et al., 2022). For each RSLR scenario, we generated an accelerating RSLR curve (based on formulations from Rohling et al., 2013), which results in an amount of total RSLR by 2100 and 2150 equivalent to those in Sweet et al. (2022). Because Sweet et al.'s (2022) RSLR projections start in reference to the year 2000 and end at 2150, our modeled RSLR rates correspond to projections for 2025-2125, allowing us to run the model for 100 years.

Storms

Storm events are a crucial driver of barrier island evolution (Dolan & Godfrey, 1973; Leatherman, 1979; Morton & Sallenger Jr, 2003). Because storm stochasticity impacts future island evolution (Reeves et al., 2021; Anarde et al., 2024a), we generated representative historic storms for use in hindcasts and synthetic storm time series for future use in runs. Using simulated historic water level and wave data, along with local beach characteristics, we created a record of storm events using a modified version of Wahl et al. (2016)'s multivariate sea-storm model (also used in Reeves et al., 2021 and Anarde et al., 2024a). To generate the required input data, we downloaded 40 years (1980 – 2020) of water level (Luettich et al., 1992) and wave data (Dietrich et al., 2011) from the ADCIRC-SWAN reanalysis data portal (*RENCI/NOAA Reanalysis Project Documentation*, 2025) for a point ~2.3 km offshore of Ocracoke. We also calculated Ocracoke's mean beach slope and berm elevation from a LiDaR DEM collected in 1997 (Office for Coastal

Management, 2023a) using the software program Automorph (Itzkin et al., 2020). Using hourly water-level (ADCIRC), significant wave height (SWAN), and wave period (SWAN) data, the multivariate sea-storm model identifies historic storms as periods of time (8+ hours) when the total water level (Rhigh) exceeds the island berm elevation. Rhigh is the sum of the ADCIRC measured water level and the maximum 2% exceedance of runup (Stockdon et al., 2006) calculated from beach slope and SWAN wave period and significant wave height. Applying these inputs, we generated a 40-year empirical record of storm events for Ocracoke. The ADCIRC-SWAN reanalysis tends to underestimate hurricane water levels because the forcing data from the European Center for Medium-Range Forecast (ECMRF) ERA5 meteorological reanalysis underestimates hurricane wind speeds (Campos et al., 2022; Chen et al., 2024; Magnusson et al., 2019). For this reason, we adjusted Rhigh by 20% for historic storms occurring between June and November (hurricane season) when Rhigh exceeded 1.75 m (NAVD88), based on sensitivity tests during hindcasts, which indicated a 20% increase in Rhigh allowed CASCADE to best predict historical island evolution.

For future runs, we used the empirical storm record resulting from the process described above to generate 10,000 synthetic storms using a vine-copula model within the modified multivariate sea-storm model (Reeves et al., 2021). From the 10,000-storm distribution and following the methods of Reeves et al. (2021), we randomly generated 100 different synthetic storm sequences which we used for all future runs. This allowed us to run each of the 18 future scenarios 100 times yielding a range of behavior across different storm sequences and intensities.

4. Model Calibration and Testing

Before applying CASCADE to future runs, we conducted hindcast simulations to calibrate the model and test model skill. For this purpose, we divided our 46-year long hindcast

into two periods: a calibration period (1974 – 1997) and a test period (1997 – 2020). For the calibration hindcasts, we used comparisons with observations (discussed below) to guide adjustments to model parameters to best replicate historical shoreline behavior and the timing and type of management actions implemented. During the test period, we applied the calibrated model parameters to the more recent time period and compared with observations to assess model skill.

4.1 Observational Data for Comparison to Hindcast Model Output

We calculated oceanside shoreline change rates in Python at a spacing of 100 m for the calibration and test period using shoreline positions from 1974, 1988, 1997, 2009 from Kratzmann et al. (2017) and a 2019 oceanside MHW shoreline extracted from a LiDaR DEM (OCM Partners, 2024) in ARCGIS Pro. We then averaged rates alongshore within the limits of each model domain to calculate shoreline change rates for the calibration period and the test period.

Using archival permits issued by the Seashore, we compiled a record of management actions undertaken to maintain access along NC 12 on Ocracoke between the Village and the northern end of the island between 1974 and 2020 (Table 1). These permits recorded the location and timing of dune construction, roadway relocation, and the emplacement of sandbags.

4.2 CASCADE Inputs for Hindcasts

We used the empirical storm record for the calibration and test periods. Because the empirical storm record begins in 1979, we created a synthetic storm sequence for the 1974 – 1979 portion of the calibration period by randomly sampling our 10,000 synthetic storms.

Relative sea level rise rates come from the Oregon Inlet NOAA gauge (8652587), the closest tide gauge located in similar conditions for the calibration and test periods.

We derived initial island topography for the calibration and test periods by combining elements of the two oldest available LiDaR DEMs, which were collected in 1997 and 2009. Because the 1997 LiDaR DEM only extended ~200 m landward of the foredune line, we merged the dunes and seaward portion of island topography from 1997 with the island interior elevations from 2009, keeping 1997 values wherever the DEMs intersected.

During the test and calibration simulations, management actions in CASCADE (artificial dune construction, washover removal, sandbag emplacement, and roadway relocation) occur dynamically in the model (as described in Section 2.2) according to user-specified thresholds (outlined in Section 4.1.1). Because NCDOT did not utilize sandbags until 2019, we disabled sandbag emplacement for the calibration period but enabled it for the test period.

4.3 Model Calibration

During the calibration period, we modified CASCADE's input parameters to best replicate observed historic behavior between 1974 and 1997. Running CASCADE in native form without any adjustments did not capture background shoreline accretion in Domain 39 or alongshore sediment contributions into Domain 1 from upstream and resulted in underestimations of oceanside shoreline erosion in Domains 21–35, and no instances of roadway rebuilding or dune construction.

Hatteras Inlet, located at the northeastern end of Ocracoke, historically serves as either a source or sink of sand to the immediately adjacent shoreline, and thus alters the geomorphic evolution of the island in our study area. Because CASCADE does not directly simulate inlet

processes, we approximate the effect of inlet-driven oceanside shoreline erosion (accretion) by determining the sink (source) value for the domain closest to the inlet (Domain 39) that best captures the effect of the inlet on observed oceanside shoreline erosion. We found that using a sediment source of +40m/yr best replicates the observed oceanside shoreline change between 1974 and 1997. Because the inlet contributed to additional background erosion (instead of accretion) during the test period, matching the observed shoreline change rates more accurately for 1997 –2017 required changing the sediment source term to a sediment sink of -20 m/yr.

Because the future effect of the inlet on background shoreline change rates adjacent to the inlet is uncertain, we modeled both the source and the sink condition for each future scenario. Although in Domain #39 the inlet caused substantial shoreline accretion between 1974 and 1997 and erosion between 1997 and 2020 (Figure 3), when considering the entire 46-year timespan, the shoreline in Domain 39 eroded at an average rate of 2m/yr (linear regression shoreline change rate; LRR). Because our hindcast inlet data span only a 23-year period (1997–2020), and the inlet may fluctuate between causing net shoreline erosion vs accretion over the next 100 years, we applied more conservative source/sink terms during future runs than during the hindcast period, using a sediment source term of +20 m/yr to represent the accretional-background inlet effect and a sediment sink term of -10 m/yr to represent the erosional-background inlet effect.

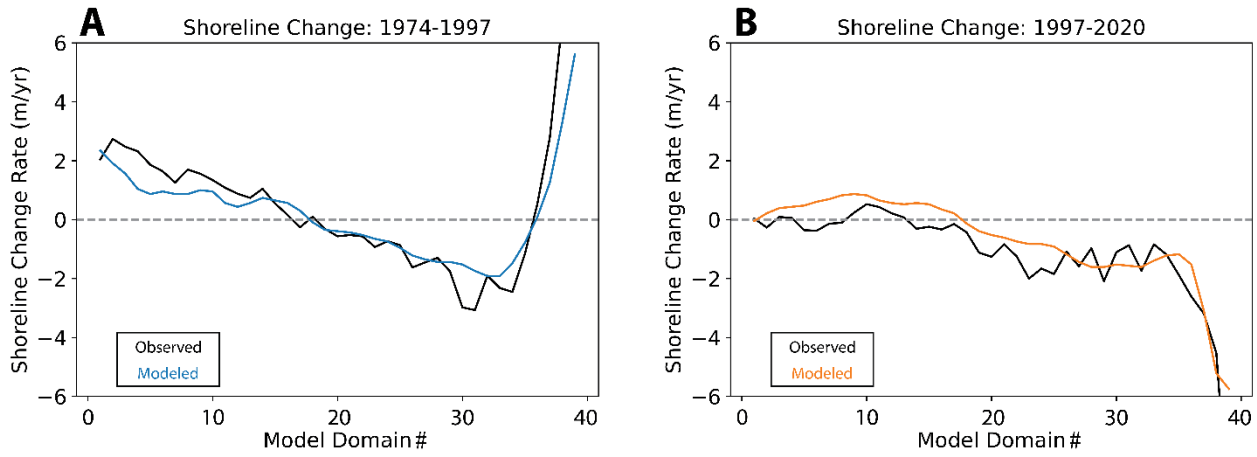


Figure 3: Comparison between observed and modeled shoreline change rates for the two hindcast periods. (A) Shoreline change rates for 1974 – 1997 represented by the hindcast calibration period and (B) shoreline change rates for the test period representing 1997 – 2020.

To determine the necessary value of a sediment source term to represent the mid-island alongshore sediment transport gradient in Domain 1, we conducted a series of sensitivity tests and found that applying a sediment source of +33 m/yr to Domain 1 resulted in shoreline accretion rates similar to historical observations. Adding the sediment source terms in Domain 1 and 39 improved the accuracy of our calibration hindcast but underestimations of shoreline erosion in Domains 21 – 35 persisted. Generating shoreline change patterns that match the observed change required sink terms that vary gradationally across domains, with a beginning value of -2.4 m/yr in Domain 35 and decreasing by increments of -0.1 m/yr per domain until Domain 21. This gradational change in the sediment sink term is consistent with the effects of a subaqueous tidal delta, such as the one associated with Hatteras Inlet. By dissipating wave energy and refracting waves, a subaqueous delta will produce a partial wave shadow, and therefore net alongshore sediment flux will tend to increase away from the inlet leading to increased erosion (Murray et al., 2020).

In the final calibration run, incorporating all adjustments, CASCADE produced shoreline change patterns similar to historical observations (Figure 3a), yielding accretion in Domains 1 – 18 and erosion in Domains 19 – 35. Additionally, dune construction and roadway relocation events occurred in the calibration at similar times and locations as in the historic record, with the calibration hindcast and historical record including one instance of roadway relocation and three instances of dune construction (Table 1).

4.4 Model Testing

Using the domain-specific sink values derived from the calibration process, the 1997 – 2020 empirical storm record with the 20% increased Rhigh value for storms above 1.75 m (NAVD88) occurring between June and November, test simulations generally replicated the observational record except near the tidal inlet. Including the modified sink term for Domain 39 to represent the change from an accretional background effect of the inlet to an erosional one, CASCADE successfully replicates the general pattern in observed shoreline change during the test period across all domains, with a slight underprediction of shoreline erosion in Domains 1 – 23 (Figure 3b). CASCADE predicts sandbag emplacement at the same time and in the same locations (within the erosion hotspot) as indicated by the permit record (comparing historic records to equivalent model years). Although the test hindcast underestimates the number of instances of dune construction (Table 1; 7 historic vs. 4 model), it correctly predicts their location and the lack of roadway relocation (0 historic vs. 0 model) during the test period. Importantly, where the test period hindcast and observations diverge, CASCADE tends to be slightly more conservative than observations, which is preferable to overprediction.

5. Development of Future Scenarios and Inputs

5.1 Management Strategies

We modeled three different combinations of management strategies: 1) maintaining historic management actions which involve artificial dune construction, removal of washover deposited on roadways, sandbag emplacement, and roadway relocation (hereafter referred to as the Status Quo Management Strategy (SQ)); 2) preventing erosion through beach nourishment, in combination with artificial dune construction (hereafter referred to as the Beach Nourishment Management Strategy (BN)); and 3) cease all roadway management actions, allowing natural processes to occur, as in the case of a causeway, bridge or ferry alterative (hereafter referred to as the Roadway Alternative Management Strategy (RA)).

Because most of Ocracoke is located within the Seashore, we limited the application of management actions in the dune and interior cells of CASCADE to within 20 m of the roadway, to approximately reflect NCDOT's highway easement. We specified artificial dune building to an elevation of 3 m above the roadway when dune cells fall below an elevation of 1.75 m (relative to the roadway). Because roadway elevation relative to sea level decreases over time as sea level rises, the absolute elevation of the dune-rebuilding threshold and designed dune elevation decrease over time, however artificial dunes are always built to a minimum elevation of 2.4 m (MHW), ensuring some protection for the roadway. If dune cells are lower than the rebuilding threshold but are more than 20 m away from the roadway (outside NCDOT's easement), we set CASCADE to construct 'dunes' in the island interior cells directly seaward of the road.

We set sandbag emplacement to occur when the roadway is less than 10 m landward of dune cells, and dunes in those cells have an elevation at or below 2.45 m (MHW). Sandbag emplacement in CASCADE rebuilds dune cells at or below this threshold to an elevation of 2.45

(MHW) and classifies them as unerodable (meaning they maintain their elevation during storms). Following the general CASCADE rules for roadway relocation outlined in Section 2.2, the roadway will be relocated 30 m landward when oceanside shoreline erosion removes the current roadway position, roadway elevation is at or below 0 m (MHW), or 20% of cells adjacent to the roadway are below 0 m (MHW).

At the request of members of the project team, we ran an additional modified version of SQ in which the roadway in Domains 21 – 39 (area of chronic erosion at the northeastern end of Ocracoke) is preemptively moved landward and elevated (See supplement for results and details). Because local stakeholders are not considering altering current barrier island management approaches along the middle of the island (corresponding to Domains 1 – 19), we maintained SQ management for Domains 1 – 19 and Domains 1 – 20 for the BN and RA runs respectively (Figure 3). We utilize SQ management in Domain 20 for RA to reflect maintenance of roadway access to a proposed ferry terminal located in back barrier of Domain 20 in this scenario.

Under BN, a nourishment event is triggered, adding sand to the shoreface, when beach width decreases below 30 m across two contiguous model domains (equivalent to a 1-km long section of island). During each nourishment event, CASCADE adds 100 m^3/m of new sand to the shoreface (50,000 m^3 per domain), resulting in ~20 m of instantaneous beach progradation due to relaxation of the shoreface profile (see Anarde et al., 2024a). Because dunes are constructed to protect a fixed roadway, the seaward limit of dunes is preserved despite beach widening. As in SQ, dunes are rebuilt to an elevation of 3 m during nourishment events if they are below 1.75 m in elevation.

Combining the three management strategies (SQ, BN, RA) with the three RSLR rates (IL, I, IH), and two background inlet effects (erosional, accretional), yields 18 unique scenarios. Because storm stochasticity greatly impacts barrier island evolution (Reeves et al., 2021; Anarde et al., 2024a) we ran each scenario with the 100 different synthetic storm sequences described in Section 2.1.3. This approach generates a range of behavior for each scenario that accounts for uncertainty in the sequencing and intensity of future storms.

6. Results

For the six scenarios associated with each management strategy, we summarize the relative differences that arise in island morphology, the timing and location of roadway-corridor fragmentation, and the timing and location of the initiation of island drowning as a function of differences in RSLR (IL, I, IH) and background inlet effects (erosional, accretional). Because we ran each of the scenarios 100 times, the sections below describe model behavior for each scenario averaged across 100 runs. We define roadway-corridor fragmentation as occurring when CASCADE cannot, following the rules defined in Section 2, maintain a roadway across all model domains, leading to a break in roadway connectivity. As noted previously, we define the initiation of island drowning as occurring in the model when all interior cells (landward of the dune) within a barrier interior fall below 0 m (MHW). Because our focus is on roadway management, the initiation of island drowning figures are presented in the supplement.

6.1 Status Quo (SQ)

Across all six SQ scenarios, the island narrows because of oceanside shoreline erosion and soundside inundation (Figure 4, 5). Under higher rates of RSLR, narrowing occurs faster,

regardless of background inlet effects. The accretional background inlet effect results in less oceanside shoreline erosion in Domains 30 – 39 (Figure 5) relative to the erosional-background inlet effect (Figure 4).

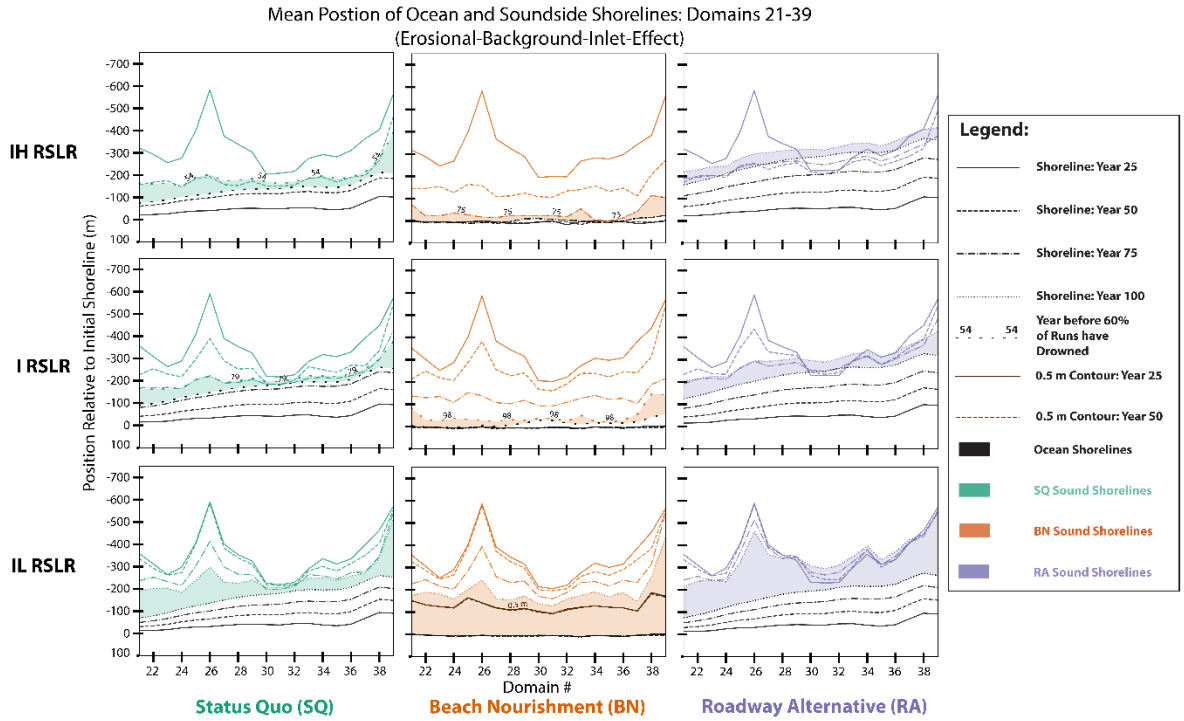


Figure 4: Location of mean oceanside and soundside shoreline positions at 25-year intervals for three management strategies, three RSLR rates, and the erosional background inlet effect. Shaded area represents the mean final island area after 100 years or after 60% of simulations have drowned (See supplement for details on the calculation of mean shoreline position). The average 0.5 m MHW contour for the beach nourishment management strategy and Intermediate-Low RSLR at 25-model years and 50 model years shows that although the island appears wide, much of it is only just above still water level.

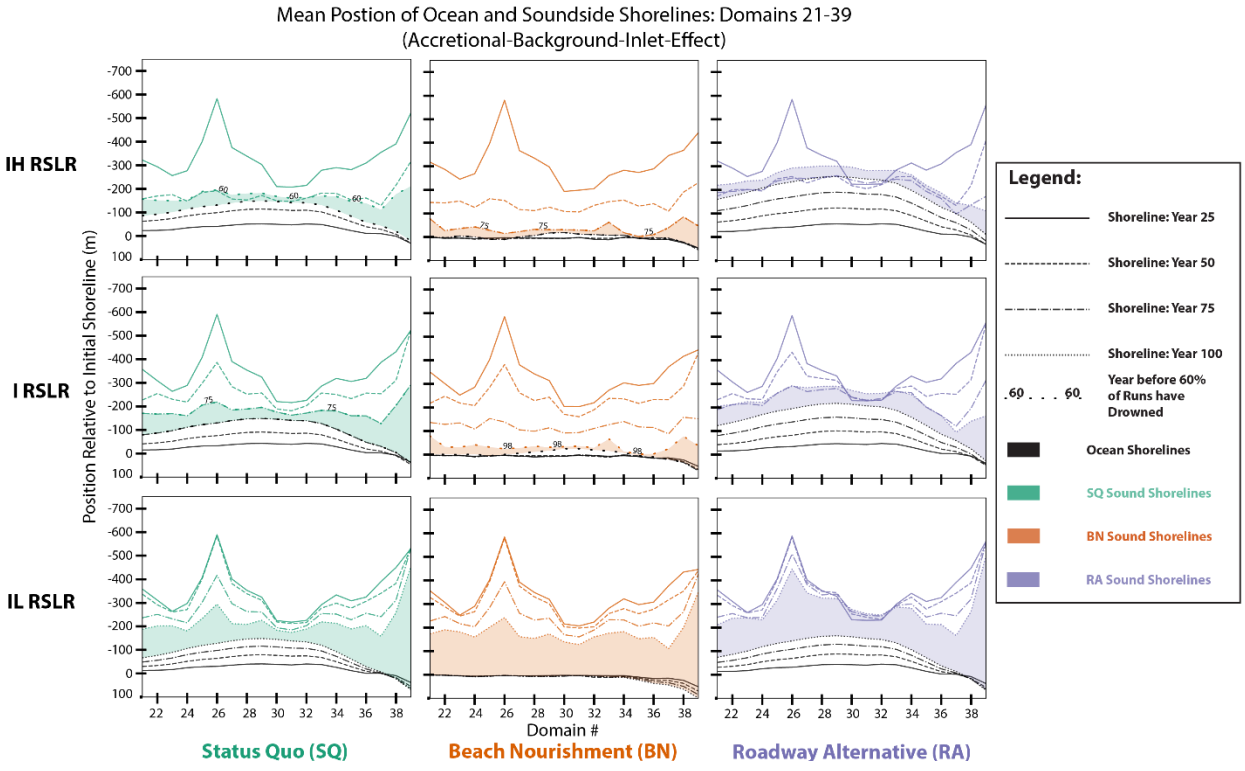


Figure 5: Location of mean oceanside and soundside shorelines at 25-year intervals for three RSLR rates, three management strategies, and an accretional-background inlet effect. Shaded area represents the final mean island area after 100 years or once 60% of simulations have drowned.

The timing of roadway-corridor fragmentation is highly dependent on RSLR rates (Figure 6). Fragmentation occurs in 100% of IH runs by model-year 50, compared to 100% of I runs and ~70% of IL runs by model-year 75. By model-year 100, fragmentation occurs, at least in many domains, in 100% of all IL, I, and IH runs. For IL runs with the erosional-background inlet effect, fragmentation commonly occurs in Domains 1, 2, 6, 7, 12 – 16, 19, 23 – 38 (Figure 7). For IL runs with the accretional-background-inlet effect, roadway-corridor fragmentation occurs comparatively less often in domains closest to the inlet relative to the erosional-background inlet effect, with fragmentation restricted to Domains 1, 2, 6, 7, 12 – 16, 19, 23 – 31

(Figure 8). Fragmentation occurs in every domain for all I and IH runs regardless of the background inlet effect.

Higher rates of RSLR cause the initiation of island drowning to occur sooner for SQ runs than in runs for the other two management scenarios (Figure S2). For IL, I, and IH RSLR runs, the initiation of island drowning rarely occurs before model-year 50. By model-year 75, the initiation of island drowning occurs for 54% of I runs and 87% of IH runs. After 100 model years, the initiation of island drowning occurs in 15% of IL, 91% of I, and 100% of IH runs. For IL, I, and IH runs, the initiation of island drowning is concentrated near the erosion hotspot for the erosional- (Figure S4) and accretional-background inlet effects (Figure S5); During I and IH runs with the erosional-background inlet effect, comparatively more drowning occurs near the inlet compared to the accretional-background inlet effect (Figure S4, S5).

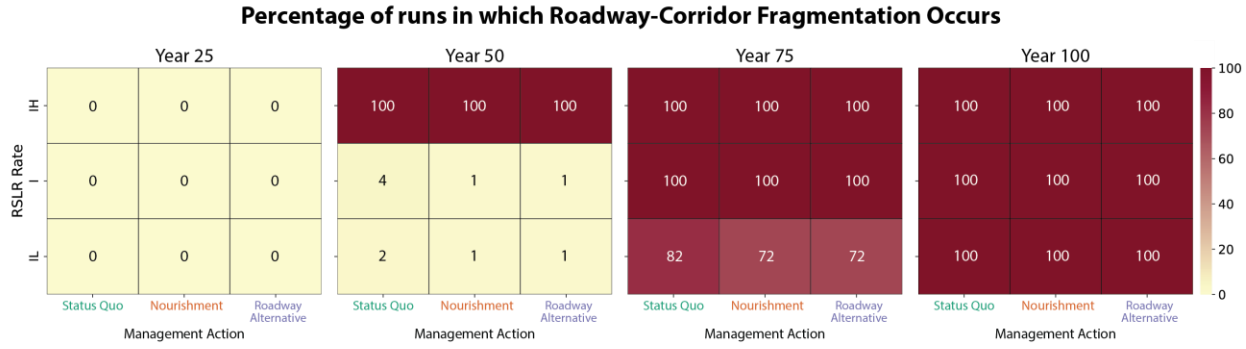


Figure 6: Heat maps showing the percentage of model runs in which roadway-corridor fragmentation occurs by model-year 25, 50, 75, and 100.

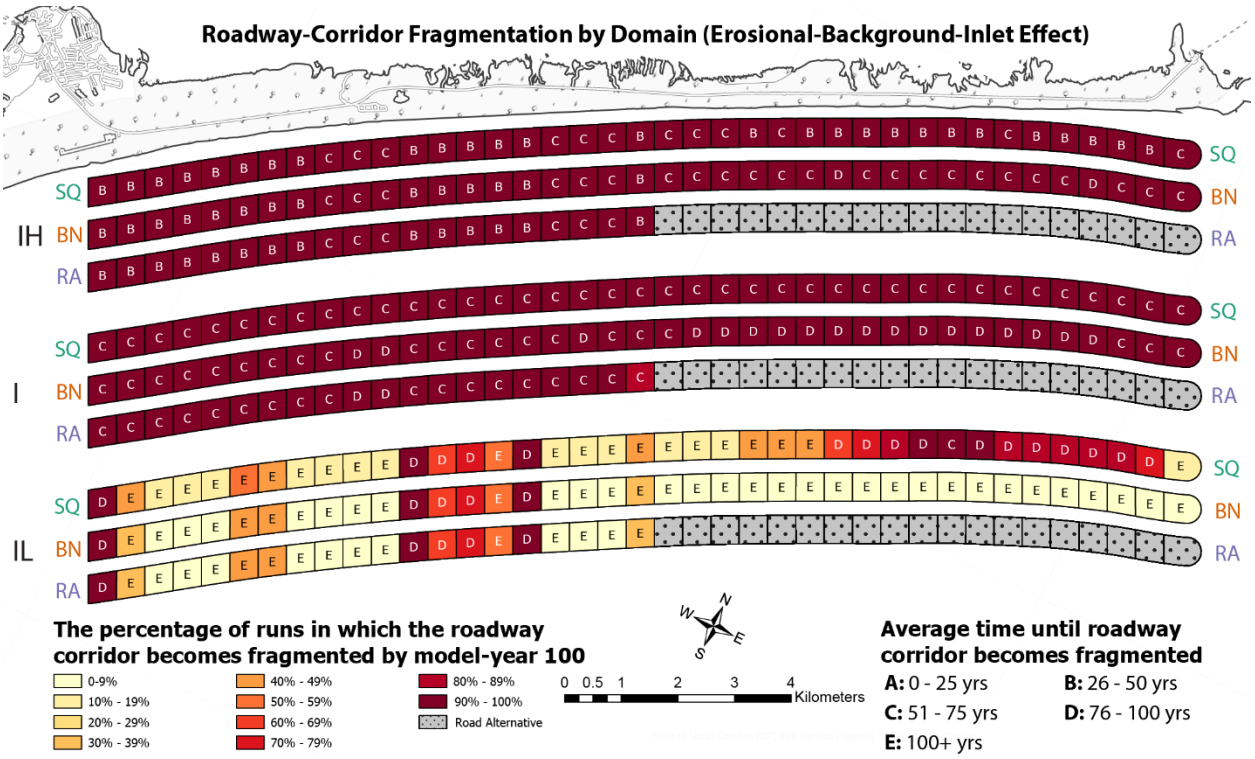


Figure 7: Model domains, with colors representing the percentage of runs in which the roadway becomes fragmented within 100 model years. Letters show the average time until the roadway becomes fragmented for Intermediate-low (IL), Intermediate (I), and Intermediate-high (IH) RSLR, Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management strategies, and the erosional-background inlet effect.

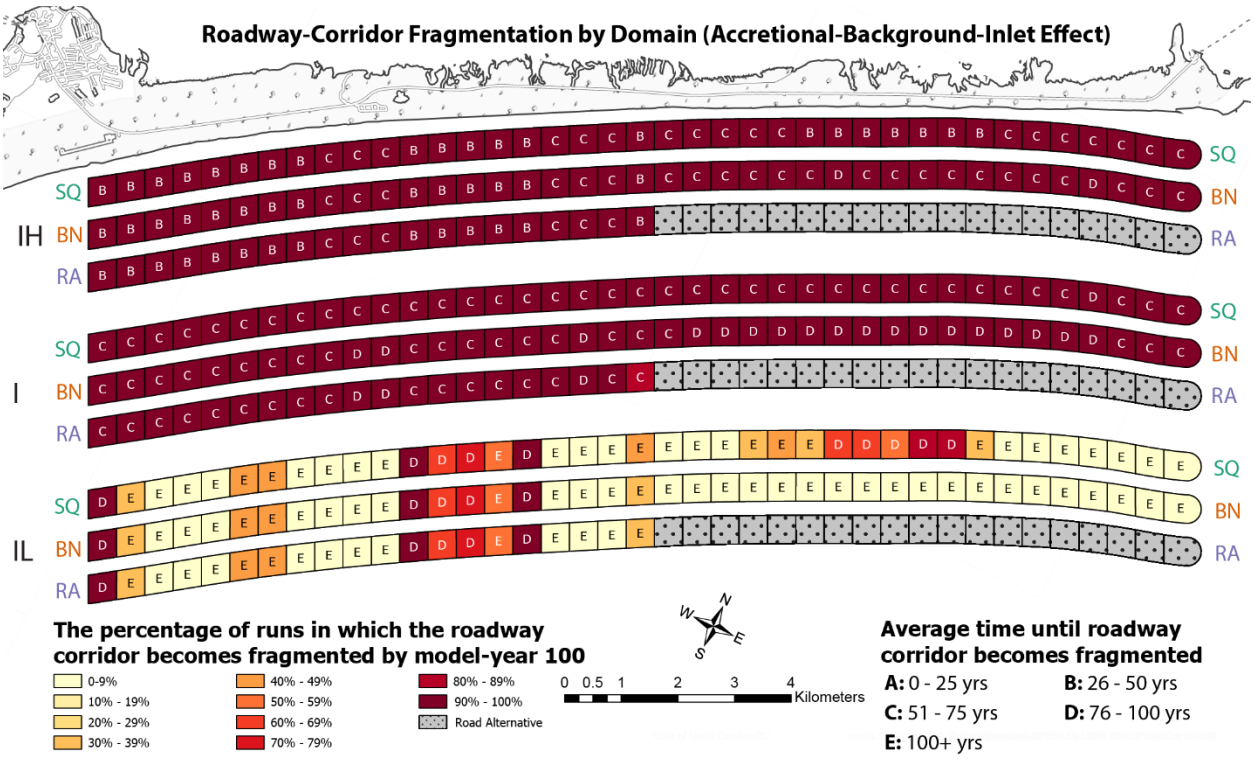


Figure 8: Model domains colored by the percentage of runs in which the roadway corridor becomes fragmented within 100 model years. Letters show the average time until the roadway becomes fragmented for Intermediate-low (IL), Intermediate (I), and Intermediate-high (IH) RSLR, Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management, and an accretional-background inlet effect.

6.2 Beach Nourishment (BN)

Across all six BN scenarios, oceanside shoreline erosion is mitigated in Domains 20 – 38, however the island still narrows over time because of soundside inundation. For both background inlet effects, the island narrows faster under higher RSLR rates (Figure 4, 5). Across the three BN scenarios with the accretional-background inlet effect, minor shoreline accretion in Domains 32 – 39 also occurs (Figure 5). Under Intermediate-low RSLR the island appears wider at 100 years than it does in the other two scenarios. The 0.5 m contour shown for BN at IL RSLR at 25

model years and 50 model years highlights that much of the additional width is low-lying and easily inundated during the tidal cycle, wind events and storms (Figure 4).

For all six BN scenarios, roadway-corridor fragmentation is highly dependent on RSLR rates (Figure 6). Fragmentations occurs in 100% of IH runs by model-year 50. By comparison, fragmentation occurs in ~60% of IL runs and 100% of I runs by model-year 75. By model-year 100, fragmentation occurs in all six BN scenarios. For IL RSLR runs with either background inlet effect, the BN management strategy prevents roadway-corridor fragmentation in Domains 21 – 29; roadway-corridor fragmentation occurs only in Domains 1, 2, 6, 7, 12 –16, 19 (Figure 7, 8). Across all I and IH runs, fragmentation occurs in every model domain by model-year 100 regardless of the background-inlet effect.

The initiation of island drowning does not occur in any of the BN scenarios before model-year 50 (Figure S2). The initiation of island drowning occurs by model-year 100 in 98% of I and 99% of IH runs. For BN scenarios in which the initiation of island drowning occurs, the location of island drowning initiation is concentrated near the erosion hotspot (Figure S4, S5).

6.3 Roadway Alternative (RA)

Across all RA scenarios, the island narrows over time from a combination of oceanside shoreline erosion and soundside inundation, with higher rates of RSLR causing more rapid island narrowing (Figure 4, 5). For runs including the accretional-background inlet effect, oceanside shoreline erosion is reduced in Domains 31– 39 relative to runs with the erosional background inlet effect. Although the island tends to narrow over time initially for all RA scenarios, most domains within the erosion hotspot begin to rollover (Figure 4).

For all RA runs, roadway-corridor fragmentation is highly dependent on RSLR. Fragmentation occurs in 100% of IH runs by model-year 50 compared to the occurrence of fragmentation in ~60% of IL runs and 100% of I runs by model-year 75. Considering all six RA scenarios, fragmentation occurs in 100% of runs by model-year 100. For IL runs with accretional- or erosional-background inlet effects, fragmentation occurs in Domains 1, 2, 6, 7, 12 – 16, 19 (Figure 7, 8). For all I and IH runs, island fragmentation occurs in every domain regardless of the background inlet effect.

Across all RA scenarios, the initiation of island drowning rarely occurs before model-year 75. By model-year 100, only 7% of I runs and 25% of IH runs include initiation of drowning (Figure S2). For all RA I runs, the initiation of island drowning typically occurs near the erosion hotspot. Under IH scenarios, the location of the initiation of drowning location varies across runs (occurring in Domains 20 – 38), with more drowning occurring near the inlet under an erosional-background inlet effect (Figure S4) than under the accretional-background inlet effect (Figure S5).

7. Comparisons and Interpretations across Scenarios

Across all RSLR rates and inlet dynamics, differences in island management strategy lead to differences in island morphology, differences in the occurrence and location of roadway-corridor fragmentation as well as differences in the timing and location of the initiation of island drowning. We summarize these relative differences in the sections that follow.

7.1 Island Morphology

Comparing across scenarios, we find that SQ and BN reduce washover deposition in the island interior relative to RA (Figure 9a). The continued construction of dunes, removal of

washover from the roadway, and emplacement of sandbags under SQ reduces washover deposition flux, preventing island rollover and elevation gain. Beach nourishment and artificial dune construction mitigate shoreline erosion, although the lack of washover deposition keeps the barrier from migrating landward and building interior elevation. The lack of overwash transport causes gradual barrier narrowing from soundside inundation. Although SQ and BN both reduce washover, BN has the least amount of washover because mitigation of shoreline erosion and dune construction have an additive effect; the dunes are less frequently eroded, and are therefore more effective at preventing washover deposition. Under RA management, although natural sediment transport processes occur the island still narrows over time from a combination of shoreline erosion and soundside inundation. However, increased washover deposition in the RA scenario along portions of the barrier near the erosion hotspot offset some soundside inundation and extend the barrier landward, leading to island rollover.

Variations in the amount of washover deposition across scenarios leads to differences in island location, shape, and size over time (Figure 9b). The decreased overwash transport associated with BN and SQ management becomes more pronounced under higher RSLR rates (Figure 10) because soundside inundation occurs more quickly and relatively more sand is needed to maintain the same island elevation. To consider the sensitivity of our results to changes in the specific thresholds and initial conditions, we briefly also explored a modified version of the SQ management strategy (including pre-emptively relocating and elevating the road) and found the modified strategy resulted in morphological and overwash outcomes similar to SQ (Figure S3).

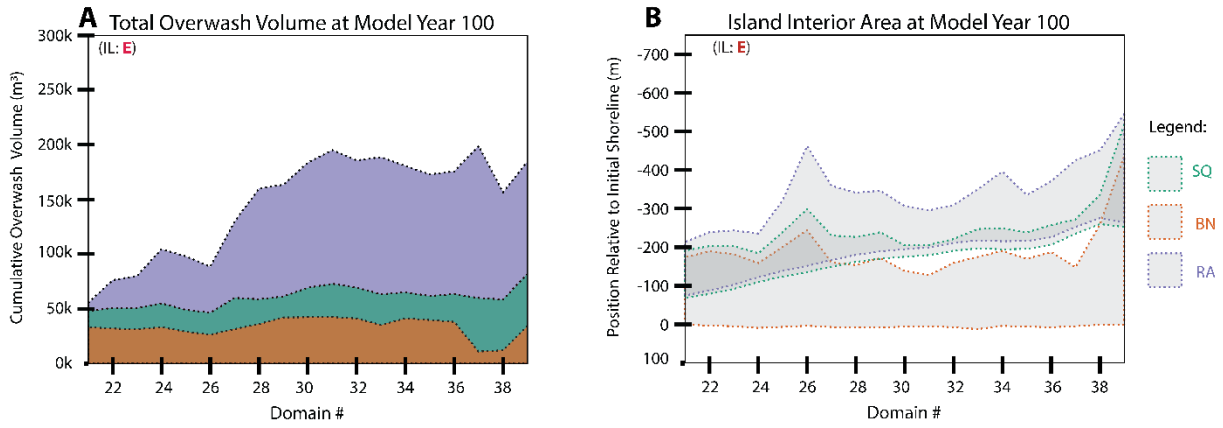


Figure 9: Barrier geometry and overwash flux for Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management strategies: (A) Mean cumulative overwash volume for SQ, BN, RA runs across Domains 21– 39 after 100 model years for IL RSLR and the erosional-background inlet effect. (B) Mean island-interior area and island location for Domains 21 – 39 after 100 model years for SQ, BN, and RA management strategies, IL RSLR and the erosional-background inlet effect.

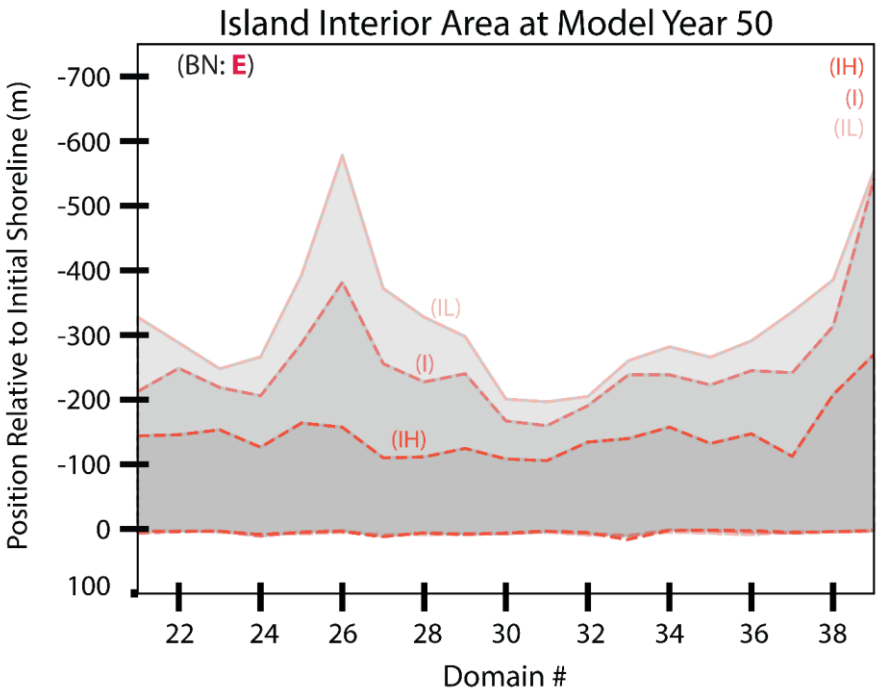


Figure 10: Mean island-interior area after 50 model years for the Beach Nourishment (BN) management strategy and the erosional-background inlet effect for Intermediate-low (IL),

Intermediate (I), and Intermediate-high (IH) RSLR rate runs. Higher rates of RSLR cause more rapid losses in back barrier island area, with the barrier narrower at higher RSLR rates.

7.2 Roadway-Corridor Fragmentation

Roadway-corridor fragmentation occurs earlier in SQ runs compared to BN runs, and in runs with higher sea level rise rates. Considering Domains 1 – 20 in which the roadway management actions are consistent across scenarios, fragmentation occurs across all domains for I and IH runs, and in Domains 1, 2, 6, 7, 12 – 16, and 20 for all IL runs, reflecting that the effects of management practices are the same in these domains.

For Domains 21 – 39, fragmentation occurs in every domain in all I and IH scenarios irrespective of management strategy and background inlet effect. Fragmentation is prevented for 100 years in Domains 21 – 39 for all BN-IL runs. Although the percentage of runs in which fragmentation occurs is similar across SQ and BN scenarios for I and IH RSLR, fragmentation occurs an average of 24 years and 19 years later in BN runs compared to SQ runs, for I and IH RSLR, respectively. Importantly, the background inlet effect influences fragmentation for SQ-IL runs with fragmentation occurring in multiple domains near the erosion hot spot under both inlet conditions, but extending to include multiple additional domains near the inlet, within 75 – 80 model years, for the SQ-IL runs in which the inlet contributes to background erosion (Figures 7, 8).

7.3 Initiation of Island Drowning

Differences in washover deposition among SQ, BN, and RA scenarios alter the timing and location of the initiation of island drowning. SQ runs result in the initiation of drowning earlier

and in more domains than BN or RA runs (Figure S3-S5), because SQ's low overwash transport causes rapid island narrowing from shoreline erosion and soundside inundation. Compared to RA, BN runs drown earlier and in more domains. Although BN mitigates shoreline erosion, BN's reduced overwash transport eventually causes drowning from soundside inundation in I and IH RSLR runs. The general location of the initiation of island drowning differs between the three management strategies (Figure S4, S5). BN runs have the most concentrated locations of the initiation of drowning, with 100% of occurrences happening in Domains 27 – 34 (near the erosion hotspot). Although the majority (70%) of occurrences of the initiation of drowning in SQ runs also occur near the erosion hotspot, a sizeable portion (11%) of runs also drown near the inlet in Domains 35 – 39. In contrast, where the initiation of drowning occurs in RA is most variable, with occurrences spread across Domains 20 – 39.

8. Discussion

This work provides further insight into the effects of barrier island management actions on decadal barrier island evolution. Below, we contextualize our model results with a discussion of the limitations of CASCADE and our approach, and a comparison of our results to other observational and modeling studies. We also address the broader applicability of our findings, and highlight the competing tradeoffs associated with barrier island management strategies.

Although CASCADE resolves the key processes of barrier island evolution including sea-level rise, storm impacts (e.g., dune scarping, overwash, washover deposition), sediment transport, and island management practices, CASCADE necessarily includes simplifications. CASCADE is designed as an appropriate complexity model (Anarde et al., 2024a; French et al., 2016), including the most important processes necessary to resolve barrier island evolution at the scale of decades to centuries and 100s of meters. Given this, and the model resolution (10 m x 10

m cells), CASCADE includes simplified beach dynamics, updating beach width annually based on nourishment volume and changes to shoreface location instead of hourly or daily wave processes. Natural dune growth is similarly abstracted, occurring according to empirically derived logarithmic growth rates (Houser et al., 2018) rather than the explicit modeling of the ecomorphodynamic and aeolian processes associated with natural dune growth (e.g., Moore et al., 2025).

To simplify representation of the effects of RSLR, CASCADE operates relative to MHW rather than the NAVD88 vertical datum. Although elevation is measured relative to a single, local MHW value, MHW can vary between the ocean and soundside of a barrier island, potentially leading to overestimations of back-barrier inundation depending on the difference in tidal range between the ocean and sound. CASCADE also adopts a simplified treatment of the soundside shoreline and the backbarrier interior; within CASCADE all soundside shoreline change is the result of passive inundation due to RSLR. Inclusion of the secondary effects of marsh accretion, barrier outwash, and soundside wave erosion is left for future efforts, which may allow finer resolution estimates of changes to back-barrier morphology. Further, as discussed earlier, our use of the terms “roadway-corridor fragmentation” and “initiation of island drowning” represents model-specific conditions, which reflect lowering of model domains or portions of model domains relative to 0 m MHW in CASCADE. Importantly, the “map-view” average island areas shown in Figures 4 and 5 include all model cells above 0 m MHW. Much of the area shown is barely above 0 m MHW, and likely to be regularly flooded by wave runup, wind-driven flow and high tides, especially given that the roadway on Ocraocke is exposed to overwash and underwash (water flowing landward underneath dunes and sandbags) on a near-weekly basis in the present day. The 0.5 m contour shown for the BN scenario under IL RSLR

illustrates this (Figure 4). An analysis of how the frequency of overwash and underwash may change in the future as a function of management scenario is beyond the scope of the work presented here, but is the subject of a forthcoming effort.

When designing the model scenarios, we chose RSLR rates, storm sequences, and background inlet effects that approximate a range of different potential future conditions, with the recognition that actual future conditions are unknown and uncertain. Our results are not meant to imply predictions of island evolution at the scale of 10's of meters. Instead, they highlight trends and qualitative differences that tend to occur in the model, based on different potential management choices and climate change effects. Further, to easily assess the relative differences in landscape outcomes among the three roadway management strategies we applied one strategy at a time for 100 years. In reality, however, management strategies may vary over time, according to new information and shifting conditions. Future investigations designed to assess adaptative management scenarios including strategies that vary over time will provide additional insight and understanding into the complexities of managing these environments. Importantly, adding representation of the effects of inlets in CASCADE demonstrates that inlet dynamics can influence the timing and location of roadway-corridor fragmentation and initiation of drowning; when an inlet contributes to background erosion, fragmentation and drowning occur sooner and closer to the inlet.

Recent observational and modeling studies support many of our findings. For example, decreases in overwash sediment flux caused by the construction and maintenance of dunes is consistent with observations of bay shoreline recession and island narrowing in other actively managed portions of the Outer Banks (Smith et al., 2008; Timmons et al., 2010). Comparing our results with observations of Ocracoke more directly reveals agreement between model results

and observed historic changes. The reduction in washover deposition associated with the construction and maintenance of dunes in CASCADE is consistent with Ocracoke's historic record; between 1944 and 2018, only four overwash events occurred on Ocracoke, suggesting that historical dune construction prevented overwash from occurring except during the most intense of storms (Conery et al., 2018). Across all scenarios, Ocracoke tended to become narrower over time in response to RSLR, which aligns with observations of historical island narrowing between 1944 and 2018 (Conery et al., 2018). Previous research (Paris & Mitasova, 2018) compares the relative geomorphic evolution of different sections of Ocracoke, attributing differences in geomorphology to variability in framework geology, with artificial dune construction serving as a secondary control. In contrast, our results explain relative changes to island morphology without invoking framework geology, instead highlighting the ways Ocracoke's morphology reflects natural overwash transport processes modified by anthropogenic influences.

Considering recent modeling studies, the faster and more frequent initiation of island drowning for SQ and BN runs compared to RA runs is consistent with previous findings, which demonstrate that protective actions associated with roadway management increase the risk of barrier island drowning (Anarde et al., 2024a, 2024b; Magliocca et al., 2011) and that developed sections of barrier islands tend to drown sooner relative to natural ones (Miselis & Lorenzo-Trueba, 2017). Differences in overwash flux (and associated washover deposition), and the rate of soundside inundation, between SQ and RA management runs are consistent with prior findings that higher dunes reduce overwash flux and enhance the tendency for island narrowing from RSLR (Anarde et al., 2024a; Reeves et al., 2021; Magliocca et al., 2011). Blocking of overwash by buildings and shrubs result in similar dynamics (Rogers et al., 2015; Lazarus et al.,

2021; Reeves et al., 2022). Also, consistent with previous work (Anarde et al., 2024a, 2024b), we found that island survival or drowning arises from internal system dynamics and initial topography and that preemptively halting roadway maintenance (represented by RA) restores natural overwash transport, allowing for island rollover and enhancing island persistence.

By tailoring our model runs to represent a specific island (Ocracoke) and actual management scenarios actively under consideration, and then varying the range of conditions considered, our results are broadly applicable to developed barrier islands generally, underscoring the range of potential effects of different management strategies on decadal- to century-scale barrier evolution. Although chosen in consultation with the project team, the selected strategies reflect common combinations of approaches to managing barrier island roadways. For example, although the specific rules and thresholds associated with the Status Quo strategy (dune construction, sandbag emplacement, washover removal and occasional roadway relocation) will likely vary with location, the general dynamics and outcomes of using these approaches to protect roadways on barrier islands will likely be similar.

Although communities will adopt different shoreline protection strategies, beach nourishment in combination with dune construction is an increasingly popular response aimed at mitigating chronic shoreline erosion. Many coastal communities in the United States regularly undertake beach nourishment projects, with 164 nourishment events occurring in North Carolina between 2000 and 2024 (Program for the Study of Developed Shorelines, 2025). Our findings indicate that, like dune construction and the built environment, beach nourishment reduces washover contributions to the barrier island interior. Ultimately, only management actions that allow overwash processes to occur unimpeded—whether a bridge, causeway, an unmanaged

sand roadway, or managed realignment and cessation of roadway management—will promote long-term island persistence and rollover as sea level continues to rise.

The future evolution of developed barrier islands will depend strongly on the strategies used to manage them, with the potential for some strategies to hasten island drowning and uninhabitability by humans. Our results highlight the challenges of meeting competing stakeholder priorities and the importance of considering potential tradeoffs involved in choosing from among the possible combinations of management actions with the hope of protecting roadways, especially in the face of legislative mandates that require preservation of flora and fauna and physiographic barrier island conditions (H.R. 7022, 75th Cong., 1937). Many stakeholders and coastal managers naturally prioritize short term considerations like maintaining existing transportation corridors, while other stakeholders and coastal managers are required to maintain and prioritize the natural functioning of the barrier island ecosystem as they make decisions. Going forward, there may be a need to consider more adaptive solutions like ferries or sand roadways that maintain transport access, while simultaneously allowing natural island processes to function.

Although barrier islands are transitory features when considered over geological timescales, the decisions made now by communities and stakeholders will have a major impact on how inhabited barriers evolve over the next 25 – 100 years. At higher rates of sea-level rise, critical transportation corridors and infrastructure will likely be impacted much sooner. Our results demonstrate that intentional decision making will require the identification and prioritization of often competing and contrasting goals for island morphology. It will be critical for coastal planners and managers to carefully consider how different management strategies will

affect barrier island width, position, and area above sea level, and consider more adaptive strategies as conditions continue to change.

9. Conclusions

Based on model simulations, we find that different combinations of artificial dune construction, washover removal from roadways, sandbag emplacement, beach nourishment, and roadway relocation, lead to variations in long-term island width and differences in the timing and location of roadway-corridor fragmentation and the initiation of island drowning. Management actions that involve actively maintaining dunes, removing washover, emplacing sand bags or nourishing beaches lead to reduced overwash transport relative to natural conditions, and therefore lower island interior elevations and enhanced soundside inundation. By reducing overwash, these actions also prevent island rollover, causing the roadway-corridor to become fragmented sooner and across a broader area, and the initiation of island drowning to occur sooner and across a broader area, relative to runs without management actions to protect a land-based roadway. The effects of decreased overwash transport become more severe under higher rates of RSLR because the mismatch between the rate of elevation increase in the island interior and the rate of sea level rise becomes more pronounced. Importantly, when the inlet at the northeastern end of the island contributes to background erosion rates (rather than offsetting them with accretion) shoreline erosion rates close to the inlet, along with the occurrence of roadway-corridor fragmentation and the initiation of drowning, all increase.

Interestingly, because beach nourishment (paired with sand bag emplacement and dune construction) mitigates oceanside shoreline erosion in Domains 21 – 39, it prevents roadway-corridor fragmentation for IL runs and delays fragmentation for I and IH runs, relative to the corresponding Status Quo runs. However, like the Status Quo strategy which does not include

nourishment, the beach nourishment strategy ultimately leads to island drowning because of its negative impact on overwash transport to the island interior. Under natural conditions, when the land-based roadway is not maintained and overwash processes occur unimpeded, model outcomes indicate the island begins to roll over near the erosion hotspot, reducing the likelihood of the initiation of island drowning.

Our results demonstrate the critical role barrier island management plays in the evolution of developed barrier islands at the scale of 25 – 100 years, highlighting how differences in overwash transport alter long-term island morphology. Going forward, managers of protected areas, coastal planners, stakeholders, and communities will face tradeoffs in managing these landscapes, making it crucial to understand both the short- and long-term costs and benefits of different management actions. Geomorphic models like CASCADE, which include the effects of management actions on the evolution of coastal landscapes, can provide science-based insights to assist in decision-making that is intentional in considering tradeoffs and working to avoid unforeseen, unintended consequences.

Data Availability Statement

The CASCADE model is available from GITHUB at https://github.com/UNC-CECL/CASCADE and an archived version of the model used to carry out this project is available on Zenodo (will add DOI once uploaded). The average model run values for each scenario used in our analysis and figure creation is archived on the University of North Carolina Core Data repository and can be downloaded and accessed here: https://doi.org/10.15139/S3/AHP4MC.

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TABLES:

Table 1: Record of historic management actions (dune construction, sandbag emplacement, roadway relocation) on Ocracoke between 1974–2020 and comparison between observed and modeled management actions during the calibration (1974–1997) and test periods (1997–2020).

	Observed: 1974–2020	**Observed: 1974–1997**	**Modeled: 1974–1997**	**Observed: 1997–2017**	**Modeled: 1997–2017**
Instances of Dune Construction	10	3	3	7	4
Sandbag Emplacement Occurs	Yes	No	NA	Yes	Yes
Roadway Relocation Occurs	Yes	Yes	Yes	No	No

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Supplement:

Preemptive Roadway Relocation Scenario:

To explore how sensitive our model results are to changes in specific model management thresholds, we created a modified version of Status Quo (SQ) management known as Preemptive Roadway Relocation (PR). Compared to SQ, PR has a modified initial roadway position, roadway elevation, and roadway relocation rules. Under PR, the roadway in Domains 21 –39 starts 30 m landward of its initial SQ location, has an initial elevation of 3 m (MHW) (compared to 1.45 m (MHW) for SQ), and has more relaxed roadway relocation rules, allowing the roadway to be maintained even when surrounded by water cells (analogous to a causeway). We run PR runs for a subset of the parameter space, choosing Intermediate RSLR (I), an erosional-background inlet effect (E), and our standard 100 synthetic storm sequences.

We find minimal differences between PR and SQ runs, with island morphology being extremely similar (Figure S3A) and both PR and SQ reducing overwash flux relative to the Roadway Alternative (RA) runs (Figure S3B), with PR decreasing overwash flux slightly more than SQ. The initiation of island drowning occurred at comparable times in PR and SQ runs, with PR runs on average drowning after 71 model years vs 78 for SQ. The similarities between SQ and PR runs demonstrate that our results are not highly sensitive to the specific values used for roadway management.

Calculating and Displaying Mean Barrier Island Characteristics

Because we ran 18 different scenarios with 100 different synthetic storm sequences, we needed to assess scenario-average island behavior across all 100 storm sequences. To calculate domain average ocean and sound-shoreline positions seen in Figures 4 and S1, we record each

domain's oceanside shoreline and sound-shoreline positions at model-year 25, 50, 75, and 100 for all 100 runs within a scenario. Because some runs had the initiation of island drowning occur before model-year 100, we only record the shoreline positions for runs which last until the listed model-year (e.g. for a run lasting 78 years, we record shoreline positions for model-year 25, 50, and 75, but not for model-year 100 because the run did not last 100 model-years). We calculate average shoreline position values for each domain at model-year 25, 50, 75, and 100 by taking the mean of each domain's recorded ocean and sound-shorelines for that time interval. To avoid survivorship bias, we stop plotting shoreline position once 80% of runs have drowned. Because we want to visualize what final island morphology looks like for scenarios where the initiation of island drowning occurs before model-year 100, we plot the final mean ocean and sound-shorelines for the year just before 60% of runs drown (e.g., if 60% of runs drown by model-year 59, show shorelines at model-year 58).

Supplement Table:

Table S1: List of management actions used in Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management.

	SQ	BN	RA
Dune Building?	Yes	Yes	No
Sandbag Emplacement?	Yes	No	No
Beach Nourishment?	No	Yes	No
Roadway Present?	Yes	Yes	No
Washover Removal from Roadway?	Yes	Yes	No

Supplement Figures:

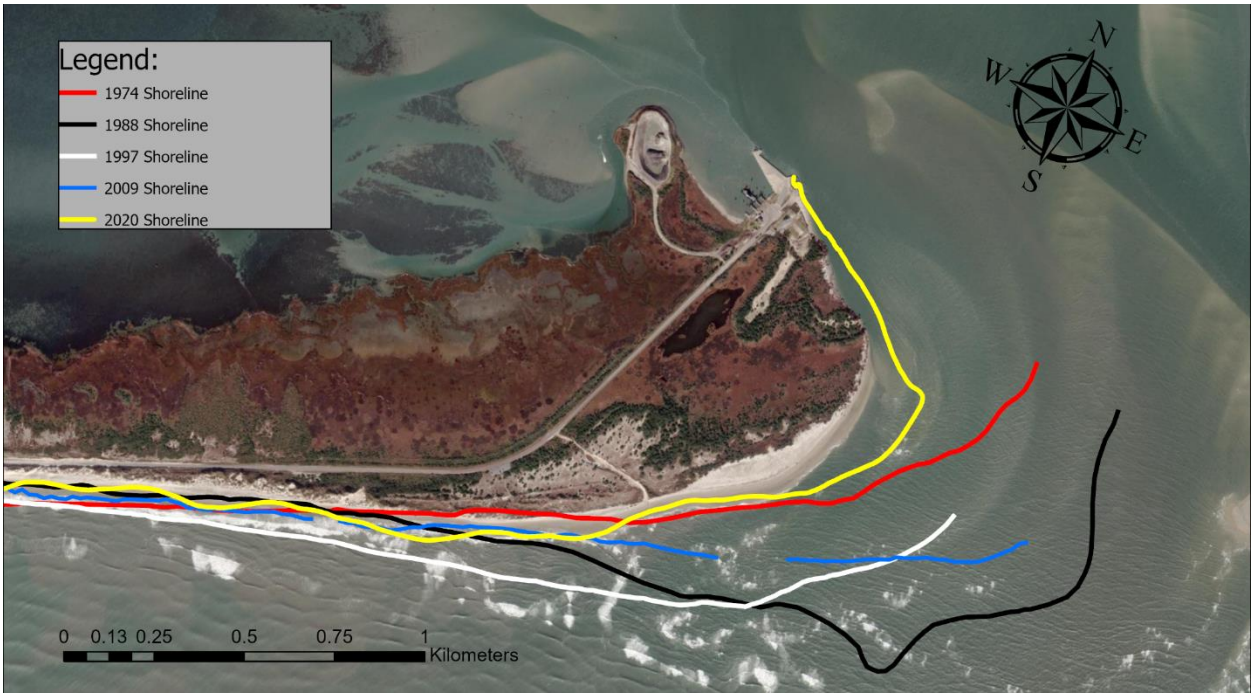


Figure S1: Location of historic shorelines on northern Ocracoke near Hatteras Inlet.

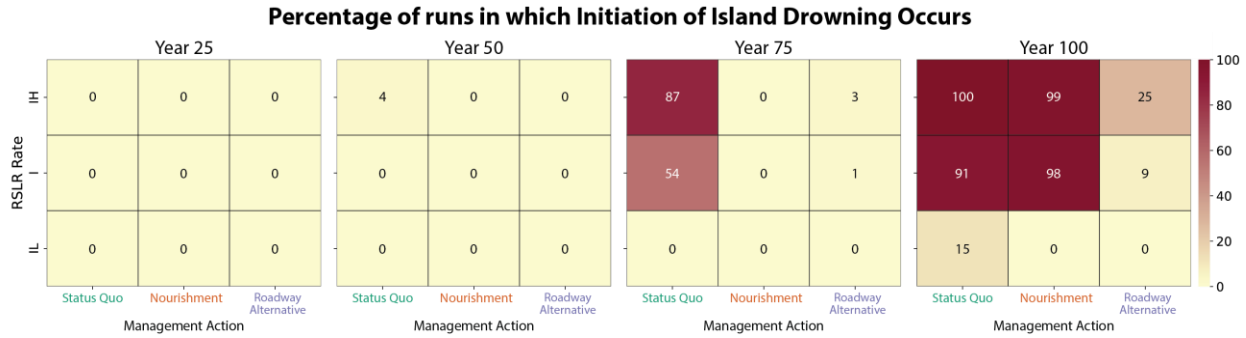


Figure S2: Heat maps showing the percentage of runs where the initiation of island drowning occurs by model year 25, 50, 75, and 100.

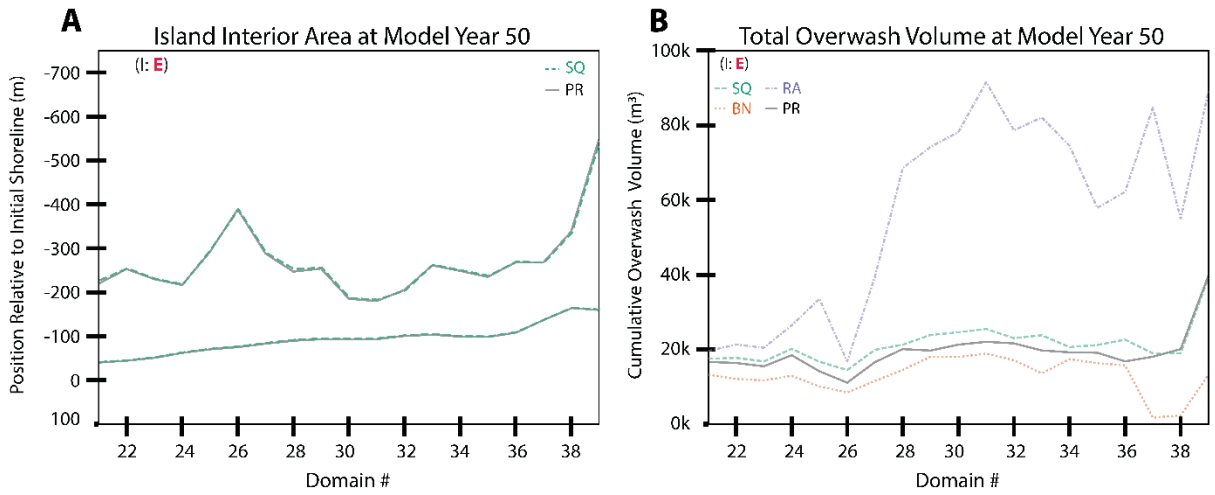


Figure S3: Comparison of Preemptive Roadway Relocation (PR) to Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management under Intermediate (I) RSLR and an erosional background inlet (E). (A) Mean island interior for PR vs SQ management runs after 50 model years for I RSLR and an erosional-background inlet effect: note the similarity in the location of SQ and PR shorelines. (B) Mean total overwash volume after 50 model years for SQ, BN, RA, and PR under I RSLR and an erosional background inlet.

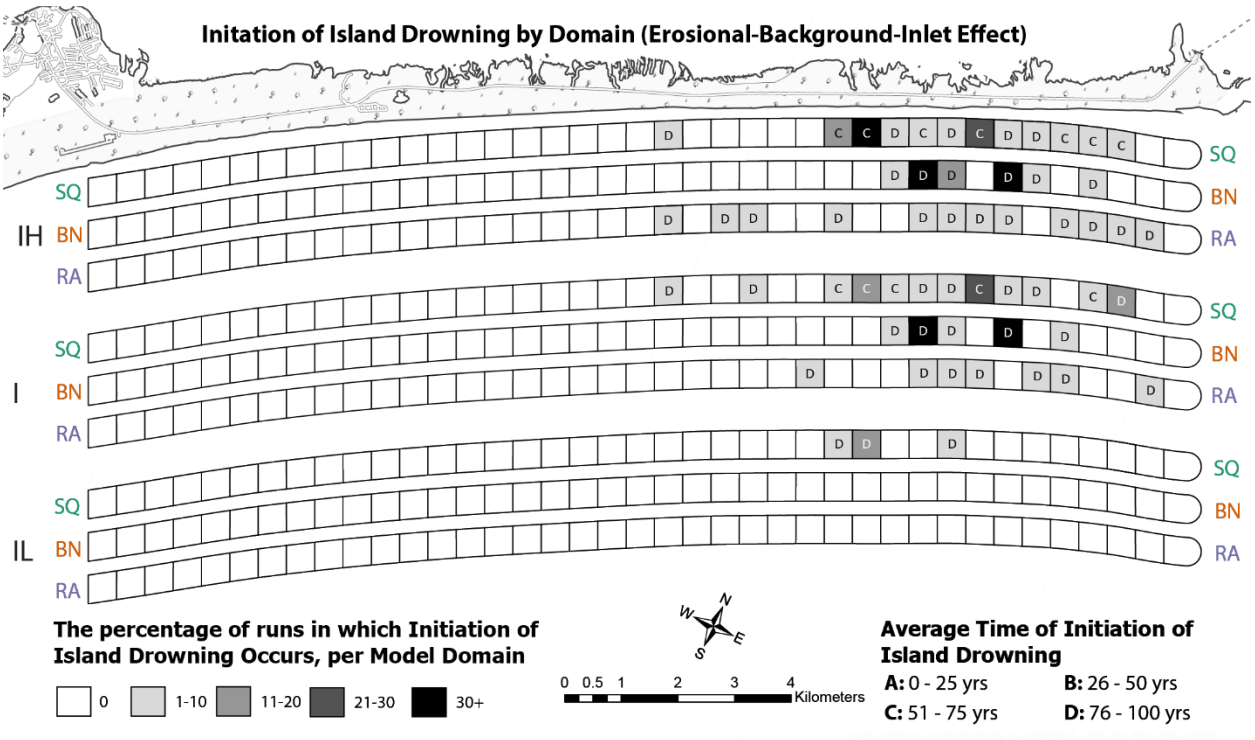


Figure S4: Model domains where the initiation of island drowning occurs for Intermediate-low (IL), Intermediate (I), and Intermediate-high (IH) RSLR rates, Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management strategies, and the erosional-background inlet effect.

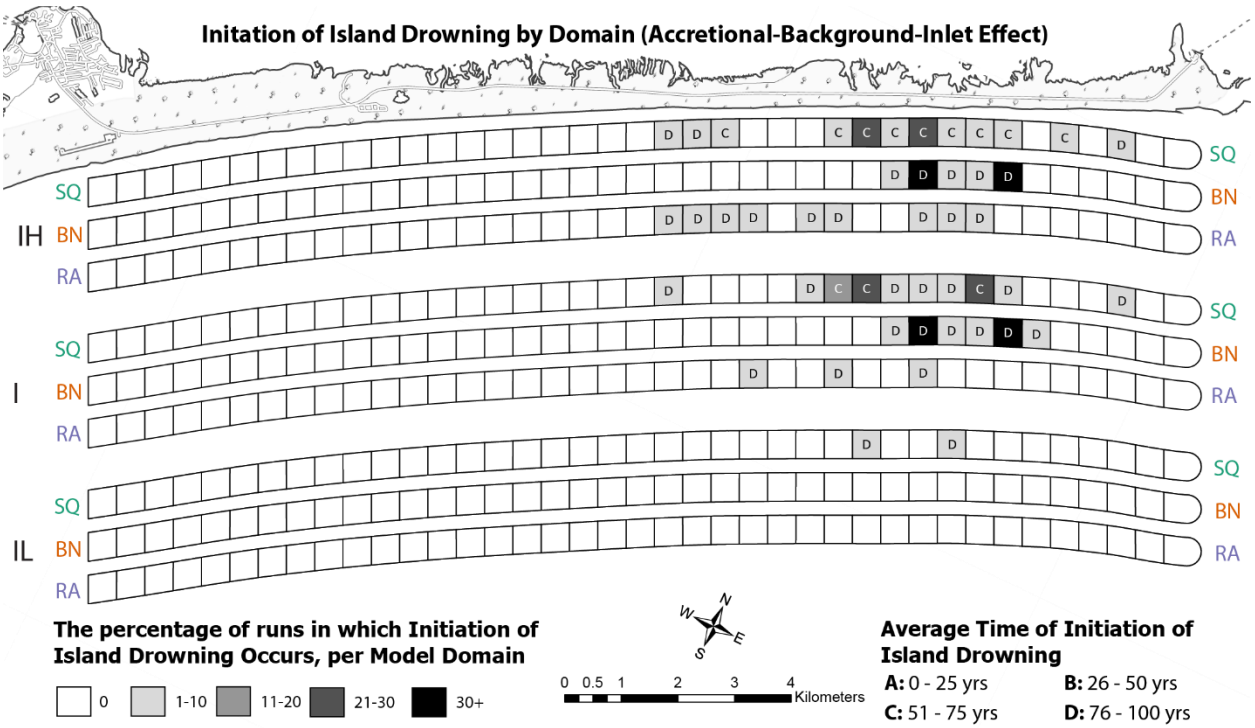


Figure S5: Model domains where the initiation of island drowning occurs for Intermediate-low (IL), Intermediate (I), and Intermediate-high (IH) RSLR rates, Status Quo (SQ), Beach Nourishment (BN), and Roadway Alternative (RA) management, and an accretional-background inlet effect.