The Future of Developed Barrier Systems: Pathways Toward Uninhabitability, Drowning, and Rebound

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Key Points:

- Dune dynamics, alongshore connectivity, and stochasticity in dune-storm interactions affect long-term outcomes of management practices
- Early, partial abandonment of developed barriers may lead to less vulnerable states, even under extreme SLR and increases in storminess
- Simulations suggest barrier systems can recover in height, width, and cross-shore position quickly (within decades) after management ceases

Abstract

Developed barrier systems (barrier islands and spits) are lowering and narrowing with sea-level rise (SLR) such that habitation will eventually become infeasible or prohibitively expensive in its current form. Before reaching this state, communities will make choices to modify the natural and built environment to reduce relatively short-term risk. Using a new coupled modeling framework, we simulate how, over decades to centuries, defensive measures to protect development (roadways and communities) alter the physical characteristics, and therefore habitability, of barrier systems. We find that the pathway toward uninhabitability (via roadway drowning or community narrowing) and future system states (drowning or rebound) depends largely on dune management – which influences overwash delivery to the barrier interior – but also on exogenous conditions (SLR and storminess), initial conditions (barrier elevation and width), and alongshore connectivity of management strategies. The timing and occurrence of barrier drowning depends on the rate of SLR and on stochasticity in the timing and intensity of storms and dune recovery processes. We find that negative feedbacks involving storms can allow barriers that do not drown to rebound toward steady-state geometries within decades after management practices cease. In the case of partial, early abandonment of roadway management (i.e., decades before the road is deemed untenable), we find that system-wide transitions to less vulnerable states are possible, even under accelerated SLR and increased storminess.

Plain Language Summary

Barrier islands and spits (collectively referred to as "barriers") can naturally keep up with sea level rise (SLR) primarily through a process called overwash. During overwash, sand from the beach is washed landward past the dunes by storm waves, which increases barrier height and width. Tall dunes, built to protect roadways and ocean front properties, prevent overwash from elevating the existing barrier landscape. Here we use a new model to show that over many decades to centuries, an unintended consequence of rebuilding tall dunes in the aftermath of storms is the lowering and narrowing of barriers. In some cases, this leads to complete drowning of the barrier interior. In other cases, once humans stop rebuilding dunes, the landscape recovers in as little as a few decades. We find that early abandonment of dune management practices along portions of barriers may prevent highly vulnerable states – such as drowning – even under extreme SLR rates and more frequent intense storms. As communities explore choices for climate adaptation, our findings reveal the importance of considering how decisions to rebuild dunes in the aftermath of storms might play out over many decades to inadvertently alter the landscape in ways that may be undesirable.

1 Introduction

Along sandy coastlines, chronic shoreline erosion resulting from alongshore movement of sediment is superimposed on sea-level rise (SLR) induced long-term erosion, which is especially important for low-lying barrier islands and spits (hereafter referred to collectively as "barriers"; Leatherman, 1979, 1983; Moore & Murray, 2018). During intense storms, waves remove sand from the nearshore seabed, beach and dunes, and deposit it on top of barriers as overwash. SLR increases the frequency of overwash deposition, tending to maintain barrier elevation (relative to sea level) and barrier width.

Humans disrupt natural patterns of overwash deposition through management practices and post-storm recovery efforts that are intended to protect infrastructure, reduce risk, and support economic activity over relatively short time scales. In the short run, benefits and services provided by the built and natural coastal environments tend to be of sufficient value to justify investment in risk-reducing infrastructure, including construction of seawalls, the addition of sand to widen beaches and build tall dunes (e.g., Nordstrom, 1994, 2004; Landry and Hindsley, 2011; Jin et al., 2021), and removal of overwash deposited on roads (Lazarus et al., 2021; Velasquez-Montoya et al., 2021) – all of which prevent the natural increases in barrier elevation that overwashed sand would otherwise provide. Without increased elevation, large storms that overwhelm artificially maintained coastal dunes have increasingly damaging impacts over time (e.g., McNamara & Werner, 2008a, 2008b; Magliocca et al., 2011). Over long time scales (decades to centuries), if barriers do not migrate upward and landward, they can drown (Gilbert, 1885; Storms et al., 2002; Moore et al., 2010; Lorenzo-Trueba & Ashton, 2014; Mellett & Plater, 2018). In contrast, when overwashed sand remains, barriers become less vulnerable to SLR and future storms (Dolan, 1980; Rogers et al., 2015; Miselis & Lorenzo-Trueba, 2017).

These human manipulations also alter regional patterns of coastline change (Slott et al., 2010; Ells & Murray, 2012; Armstrong & Lazarus, 2019), which ultimately affect future human modifications to barrier systems (Williams et al., 2013; McNamara et al., 2015; Gopalakrishnan et al., 2017). Paradoxically, investments in coastal infrastructure encourage more development in locations already at high risk to storm and climate hazards (Mileti, 1999; Turner, 2000; Werner & McNamara, 2007; Cooper & McKenna, 2009; McNamara et al., 2015; Armstrong et al., 2016; Masson-Delmotte et al., 2021). The two-way interactions between natural processes and human actions make developed barriers tightly coupled, human-natural dynamical systems (Werner & McNamara, 2007).

Modeling of decade to century-scale evolution of human-occupied barriers is limited (McNamara & Werner, 2008a, 2008b; Magliocca et al., 2011; Rogers et al., 2015; Miselis & Lorenzo-Trueba, 2017; Karanci et al., 2017; Tenebruso et al., 2022), in part because it is challenging, involving human and natural dynamics that interact across nested spatial scales, and change over time in response to shifts in climate and land use (Lazarus et al., 2016). To overcome this, previous studies have relied on simplified morphodynamic models to investigate generalized behavior. Within these exploratory model frameworks (Murray, 2003; 2013), shoreface and barrier geometries are represented by idealized (nodal) profiles, and cross-shore and alongshore processes are represented through the application of simplifying assumptions. This approach has enabled the identification of important human-natural couplings, such as emergent instabilities in barrier morphology arising from short-term hazard mitigation and policy decisions (McNamara & Werner, 2008a, 2008b); differential filtering of overwash deposition by residential and commercial development (Rogers et al., 2015); shifts in natural patterns of barrier evolution (Tenebruso et al., 2022) and increased vulnerability of developed barriers to drowning by SLR (Miselis & Lorenzo-Trueba, 2017) stemming from human interference in barrier-marsh couplings (reduced overwash delivery, lagoon dredging); and greater swings in barrier stability and more rapid barrier narrowing as a result of dune management strategies (Magliocca et al., 2011).

A limitation of these models is that heterogeneities in processes are often not resolved, especially in the alongshore dimension, despite the importance of spatial variations to barrier evolution (Reeves et al., 2021) and their likely impact on interactions with management strategies. For example, alongshore variability in dune growth and recovery regulates overwash flux and patterns of barrier retreat (Reeves et al., 2021), and therefore spatial variability in dune management may influence long-time-scale characteristics of developed barrier systems. Similarly, tidal inlets alter barrier transgression rates (Nienhuis & Lorenzo Trueba, 2019b), and stabilization of inlets by humans adds complexity to alongshore patterns of coastline change (Nienhuis, 2019).

Investigating the long-term outcomes of near-term recovery and adaptation choices is needed to facilitate our understanding of levers – actions by individuals, communities, governments, or civil society groups (e.g., buyouts, partial or full abandonment of infrastructure) – that have the potential to alter the way coupled human-natural coastal systems evolve over future decades. Improved understanding of the coupled human-natural system provides a means for identifying sets of actions, or levers, that are likely to enhance the mutual resilience of communities and landscapes, versus those that may inadvertently be maladaptive. To meet these needs, we introduce a new model framework that brings together the strengths of two existing morphodynamic models of natural barrier evolution with new formulations that simulate two sets management decisions – one representing actions taken to protect and rebuild roadways, and one representing strategies employed to protect development (communities). We use this new, coupled model to explore how management actions (i.e., dune construction, road relocation, beach nourishment, overwash removal), taken in response to changing conditions, play out over decades to centuries to influence the physical characteristics of barrier systems (i.e., width and elevation) and therefore the habitability of the landscape by humans. Our simulations are generalized and exploratory, designed to apply broadly to developed barrier systems and to provide insights into the ways in which natural processes and management actions interact to steer the long-time-scale evolution of developed barrier systems under changing SLR and storm forcing.

2 CASCADE

The CoAStal Community-lAnDscape Evolution (CASCADE) model combines elements of two exploratory morphodynamic models of barrier evolution – Barrier3D (Reeves et al., 2021) and the BarrierR Inlet Environment (BRIE) model (Nienhuis & Lorenzo-Trueba, 2019a) – into a single coupled-model framework (Figure 1). Through this coupling, CASCADE combines cross-shore morphodynamics, including shoreface dynamics and spatially varying dune erosion and overwash deposition by individual storms, and large-scale coastline evolution arising from alongshore sediment transport processes. CASCADE incorporates human actions in two separate, newly developed modules. The first module simulates strategies for preventing roadway pavement damage during overwashing events, including rebuilding roadways at sufficiently low elevations to allow for burial (instead of erosion) by overwash, constructing large dunes to protect a roadway, and relocating a road into the barrier interior when necessary. The second module incorporates management strategies for maintaining a coastal community, including beach nourishment, dune construction, and overwash removal. Below we describe the rules that govern landscape and management actions in the model framework, and the couplings that connect them.

2.1 Morphodynamic models of natural barrier evolution

Barrier3D is a spatially-explicit cellular morphodynamic model that forms the core of CASCADE. This model represents the effects of individual storm events and SLR on shoreface evolution; dune dynamics, including dune growth, erosion, and migration; and overwash deposition by individual storms (Reeves et al., 2021). Barrier3D extends the capabilities offered by previous barrier evolution models (Storms, 2003; Stolper et al., 2005; Moore et al., 2010; Lorenzo-Trueba & Ashton, 2014; Lorenzo-Trueba & Mariotti, 2017) by resolving individual storm impacts to the barrier landscape, including alongshore variability in dune erosion and washover deposition, and by representing dune dynamics. Hence, Barrier3D is well suited to simulate the long-term effects of post-storm recovery strategies, such as nourishment, that modify the barrier interior, dunes, and the shoreface.

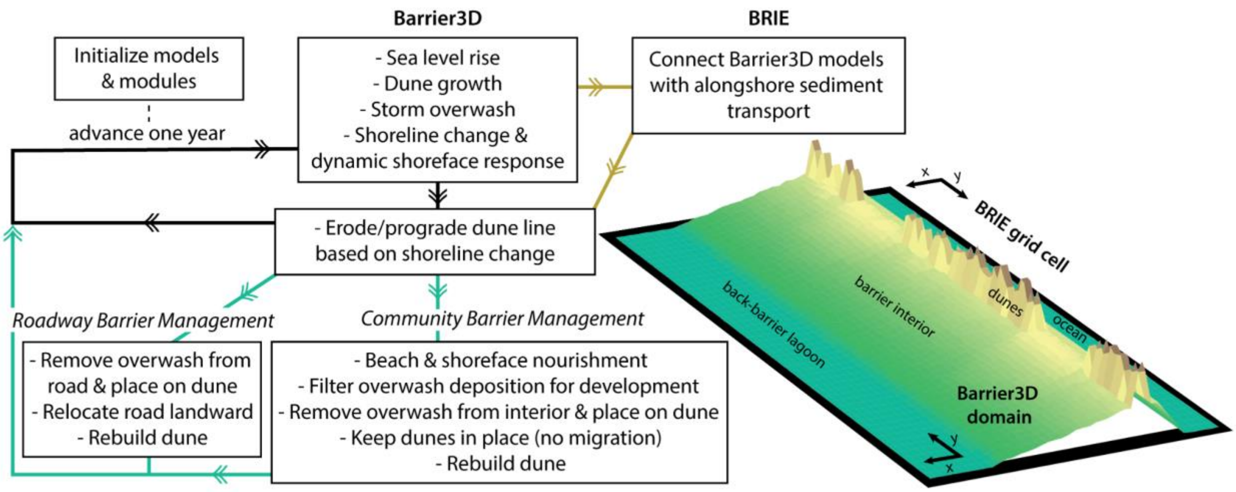

Figure 1. CASCADE time loop and coupled model domain. Two human-dynamics modules (italicized) modify the Barrier3D model domain. Green and yellow arrows indicate optional coupling pathways.

A barrier segment in Barrier3D is composed of 10x10 m grid cells. The alongshore length of the barrier segment is time-invariant, whereas the width of the barrier interior and number of cross-shore cells varies dynamically due to storm impacts and SLR. The barrier interior grid is fronted by one or more rows of dune cells (Figure 1), which follow a set of morphological rules different from those of the barrier interior. Shoreline change is simulated using a single representative cross-sectional profile for the barrier segment, following the equations of Lorenzo-Trueba and Ashton (2014), which are modified to account for dynamic adjustment of the shoreface in response to sediment lost via overwash and dune growth. Dunes can erode laterally as a result of shoreline retreat: if the ocean shoreline erodes one full cell width, the front row of the dune line is removed, and the first (most seaward) row of the barrier interior functionally becomes the back row of the active dune field. In this way, the width of the dune field is maintained as shoreline erosion occurs.

Barrier3D does not resolve beach processes and instead assumes a constant beach slope for simulation of storm water level. When storm water level surpasses the elevation of a dune cell, dune erosion scales with the depth of submergence using a predictive function developed by Goldstein and Moore (2016). Water and sediment are then routed landward into the barrier interior as overwash using a cellular flow routing scheme (Murray & Paola, 1994, 1997).

A barrier segment in Barrier3D drowns if the barrier interior elevation falls entirely below sea level. Therefore, drowning of a barrier segment can occur during a period in which the dunes are high and the barrier interior is passively inundated by SLR. It has been shown through numerical modeling (Mariotti 2021) and inferred from modern analogs (i.e., submerged shoals located seaward of barriers; Mellet et al., 2012; Rampino & Sanders, 1980; Mellet and Plater, 2018) that barrier systems can respond dynamically after width or height drowning, evolving from temporarily submerged shoals and returning to a subaerial state. Hence, drowning in Barrier3D is not necessarily representative of transition to a permanent drowned state, but rather an "effective" drowning that demarcates when the barrier interior is first submerged.

CASCADE can initialize a series of Barrier3D models, each describing a barrier segment with different initial conditions or management strategies (detailed below). The Barrier3D segments are then coupled alongshore through a diffusive wave-driven sediment transport model (with periodic boundary conditions; i.e., Ashton & Murray, 2006) housed within the BRIE model, which distributes sediment alongshore amongst the different barrier segments. This coupling is possible because both models describe shoreface and shoreline dynamics using the formulations of Lorenzo-Trueba and Ashton (2014). Functionally, this coupling of Barrier3D's cross-shore morphodynamics with BRIE's alongshore transport model requires 1) initializing both models with equivalent barrier geometry and environmental parameters, 2) separating dune migration within Barrier3D from the other model processes in the one-year time step (Figure 1), and 3) turning off all other model processes within BRIE (i.e., cross-shore barrier model and tidal inlet model). While the version of Barrier3D in the CASCADE framework produces equivalent results to the version used in Reeves et al., (2021; version testing is automated in CASCADE, see link to online repository provided in the Open Research section at the end of this paper), the default parameters are modified to match the shoreface configuration in BRIE, which depends on local wave and sediment characteristics as well as the offshore wave climate (Hallermeier, 1980; Ferguson & Church, 2004; Lorenzo-Trueba & Ashton, 2014; Ortiz & Ashton, 2016). For ease of model coupling, BRIE was rewritten in Python and both models were appended with a basic-model interface with the help of the Community Surface Dynamics Modeling System.

2.2 Human dynamics modules

Human dynamics in CASCADE are incorporated in two separate modules: a module incorporating barrier management actions optimized for protection of communities (herein referred to as community barrier management) and a module that simulates common strategies employed by entities responsible for maintaining coastal roads (herein referred to as roadway barrier management). For ease of model coupling, both modules modify the post-storm Barrier3D domain at the end of each model year (instead of after individual storms). For this reason, neither natural nor management-derived inter-storm recovery processes (e.g., dune building) nor the additional protection against storm overwash they may provide are captured. This means the amount of sediment delivered to the island interior to sustain barrier elevation and width in each module may be an overestimate. As a result, the simulated timing of barrier narrowing and lowering due to SLR is likely conservative.

2.2.1 Roadway barrier management

Transportation networks (roadways, bridges, and ferries) are the backbone of developed barrier systems: they connect communities, facilitate economic development, and provide evacuation routes. Efforts to maintain transportation networks on barriers include removal of overwash from roadways, road relocation, dune construction, and stabilization of breaches and inlets (Douglass et al., 2020; Velasquez-Montoya et al., 2021). Here we simulate strategies suggested by the U.S. Federal Highways Administration for preventing roadway pavement damage during overwashing events (Douglass et al., 2020). These include rebuilding roadways at sufficiently low elevations to allow for burial by overwash (i.e., to avoid scouring of elevated roadways); constructing large dunes to reduce the likelihood of overwashing events and to serve as a sand reservoir for the burial of roads by overwash; and relocating the road into the barrier interior. In our model simulations, all of these management strategies are implemented together until one of the following conditions are met: the barrier becomes too narrow for the road to be relocated to the island interior (i.e., <40-m wide, as detailed below), or 20% of the roadway touches water cells. Thereafter, we consider the roadway abandoned, and the barrier evolves (and potentially drowns) in accordance with the rules and dynamics in Barrier3D. Sensitivity of the timing of roadway abandonment to our abandonment criteria is discussed in the Supplement (Figure S1).

The roadway is initialized in the barrier interior at grade (i.e., at the natural elevation of the island interior), at a user-defined fixed setback distance from the landward edge of the dune line (here, 20 m), which is maintained for each instance of relocation. Road relocation is triggered when the dune line migrates onto the roadway (due to shoreline retreat). The new roadway elevation is then set to the average of the (natural) elevation of the island interior at its new location. Overwash is removed from the roadway after each model year and placed uniformly across the adjacent dune cells, simulating the localized action of earth-moving equipment. The roadway is allowed to scour; if scouring occurs, the roadway is infilled to its pre-storm elevation for that timestep. Roadway (and barrier interior) elevations decrease with SLR in accordance with the Lagrangian reference frame used in Barrier3D.

The dune line is rebuilt in the same location if the dune rebuild threshold is met. This occurs when a single dune cell falls below a specified minimum elevation at the end of each model year – which is representative of a dune gap formed during a storm. Because dunes are rebuilt to protect the roadway, and the roadway is decreasing in elevation relative to SLR, the dune rebuild threshold is set relative to the roadway elevation and therefore is likewise reduced by SLR for each time step. Consequently, for a given dune design height, dunes are not always rebuilt to the same elevation. For the case of very low-lying roadways, we do not allow the dune rebuild threshold to drop below the elevation of the berm crest (the maximum elevation of the beach, in the absence of dunes, which is time-invariant in Barrier3D). Instead, if the dune is completely eroded at the end of the model year, the dune line is rebuilt to protect the roadway (i.e., we enforce a minimum dune rebuild threshold just above the elevation of the berm crest). Dunes are also rebuilt along the seaward edge of the barrier interior if the dune line is eroded as a consequence of shoreline retreat (see discussion of natural dune dynamics in Section 2.1 above).

While artificial dune geometry can be constrained by the angle of repose, we assume the artificial dunes are built to a width capable of maintaining dunes at a specified dune design height (measured from the dune toe – here, represented by the berm elevation – to the dune crest). As detailed above, for a given dune design height, dunes are not always rebuilt to the same elevation; therefore, for the case of very low-lying roadways, when rebuilding is triggered, we enforce a minimum dune elevation of 1 m above the berm crest to ensure that the roadway remains protected.

If the rebuilt dune is higher than the natural equilibrium dune crest elevation (3.4 m NAVD88, which is equivalent to 2.9 m mean high water [MHW]; see Section 2.3), the dune is not allowed to grow naturally (i.e., we set the growth rate to zero), assuming that interactions between the dune and wind field limit sand flux and vertical dune growth (Durán & Moore, 2013). When and where dunes are below the natural equilibrium dune crest elevation, dunes are allowed to grow vertically.

The range of dune management parameters simulated herein are designed to be representative of strategies employed along North Carolina Highway 12 (NC-12), a low-lying roadway that is vulnerable to storm overwash along the North Carolina (NC) Outer Banks. The average elevation of NC-12 is 1.3 m NAVD88 and dune heights range from 2.4 to 4.6 m (dune toe to crest), or approximately 1 to 3 m above the roadway (Sciaudone et al., 2016). Roadway vulnerability assessments have shown that the dune crest must be higher than 4.3 m NAVD88 for the road to not be vulnerable to overwash (i.e., a dune height of 3 m above the roadway; Velasquez-Montoya et al., 2021). Here we simulate the effects of roadway management for dune design heights of 1, 2, and 3 m above the roadway; a 20-m wide dune line; and a dune rebuild threshold that is reached when dune elevation becomes less than 0.5 m above the roadway (with the caveats for very low-lying roadways described above). Within the model, the minimum barrier width required to sustain a roadway is set to 40 m (i.e., a 20 m-wide road + 20 m setback distance).

2.2.2 Community barrier management

In the United States, the cross-shore position of most developed barriers has not changed significantly over time, despite chronic shoreline erosion and SLR (Nordstrom, 1994, 2004; Nordstrom & Jackson, 1995). This has largely been accomplished through the use of hard structures (seawalls) or soft engineering practices (beach and dune nourishment), which protect coastal development in place (i.e., 'hold the line'). In New Jersey, the most productive state in terms of beach nourishment per meter of shoreline, sand placement amounts to approximately 7 m^3/m annually (Elko et al., 2021). After major storm events, community-focused recovery efforts can also include removal of overwash from roadways and residential and commercial properties to maintain access. Residential and commercial properties themselves also act to reduce overwash delivery to the back-barrier by obstructing overwashing flows (Lazarus et al., 2021; Rogers et al., 2015). Here, we simulate shoreline protection practices by keeping communities in a fixed cross-shore position by nourishing to maintain a wide beach. We also account for the filtering effect of development on overwash deposition and overwash removal. These management strategies and effects are employed until the barrier reaches a minimum width and can no longer sustain a community, here defined as the combined width of a single roadway and building footprint (50 m, as explained below). Thereafter, we consider the community abandoned, and the barrier evolves in accordance with the rules and dynamics in Barrier3D.

Barrier3D does not resolve beach dynamics. Therefore, we establish an initial beach width (for each barrier segment) based on the user-specified constant beach slope from Barrier3D. This beach width is then modified dynamically by nourishment and shoreface dynamics. Nourishment is triggered by a minimum beach width, which leads to placement of a volume of sand along the entire shoreface – represented in Barrier3D by a single cross-shore transect – following the formulation of Ashton and Lorenzo Trueba (2018):

$$x_{s2} = x_{s1} - (2 * v_{nourishment}) \,/\, (2 * h_b + d_s)\,, \qquad (1)$$

where h_b is the average height of the barrier, d_s is the shoreface depth, and $v_{nourishment}$ is the nourishment volume (in m^3/m). This results in a new shoreline position x_{s2}, and therefore a new beach width, and shoreface slope. Because the nourishment volume is applied to both the lower and upper shoreface, this configuration can be viewed as a relaxation of the shoreface in the months following nourishment. In contrast to roadway barrier management, in community barrier management, dune migration in Barrier3D is turned off to maintain the cross-shore position of the dune line. In this way, shoreline change (positive or negative) only affects the beach width and does not facilitate seaward progradation of the dune line with each nourishment or landward migration of the dune line with shoreline erosion into hypothetical ocean-front properties. After a community has been abandoned, we allow dunes to migrate.

As in the roadway barrier-management simulations, dunes are rebuilt when a single dune cell falls below a specified minimum elevation at the end of each model year. In the case of community barrier management, dunes serve to protect the oceanfront homes in place (at a fixed cross-shore position). Here we assume that oceanfront homeowners would expect dunes to continue to be built to the same elevation – relative to the time-invariant berm crest, which keeps pace with SLR – through time. Therefore, dunes rebuilt to protect the community are always constructed, in the model, to the same elevation. We set this elevation equal to the initial elevation of the 2-m dune design-height scenario in the roadway barrier-management simulations so that the elevation of the initial dune lines is the same (to allow comparison). Thereafter, dune management differs between the two scenarios. For community barrier management, dune rebuilding is triggered when dunes fall below 1 m in height (measured from the berm to dune crest). In combination, this time-invariant rebuild and design criteria ensures that there is always a (sufficiently large) dune present to protect ocean-front homes. As before, we do not allow dunes to grow naturally if the crest of the rebuilt dune is higher than the natural equilibrium dune crest elevation.

We account for the filtering effect of development on overwash delivery to the barrier interior by uniformly reducing the volume of overwashed sand in the interior at the end of each model year. Following Rogers et al. (2015), the overwash volume is reduced by 40% to account for filtering by residential development and 90% for commercial development. The equivalent sand volume is then added back to the shoreface using Equation 1. To simulate the return of deposited overwash sand collected from local roads, driveways, parking lots, etc. – which are not explicitly resolved in the model – we uniformly subtract an additional percentage of the overwash deposit (here, 9%) and return this volume to the dune; the remaining amount stays in place on the island interior.

Morphology thresholds used in the community barrier-management module are parameterized based on observations for Nags Head, NC, USA, a community along the NC Outer Banks that actively employs the management strategies we simulate. Thus, beach nourishment is triggered when beach width falls below 30 m, which is the average beach width in Nags Head prior to nourishment in 2011 and 2019 (Figure S2). Within the model, the minimum barrier width required to sustain a community is set to 50 m, which is approximately the sum of the minimum lot width in Nags Head (23 m), a mandated offset between the house and the road (9 m), and a single road width (15-20 m; Nags Head, 2022).

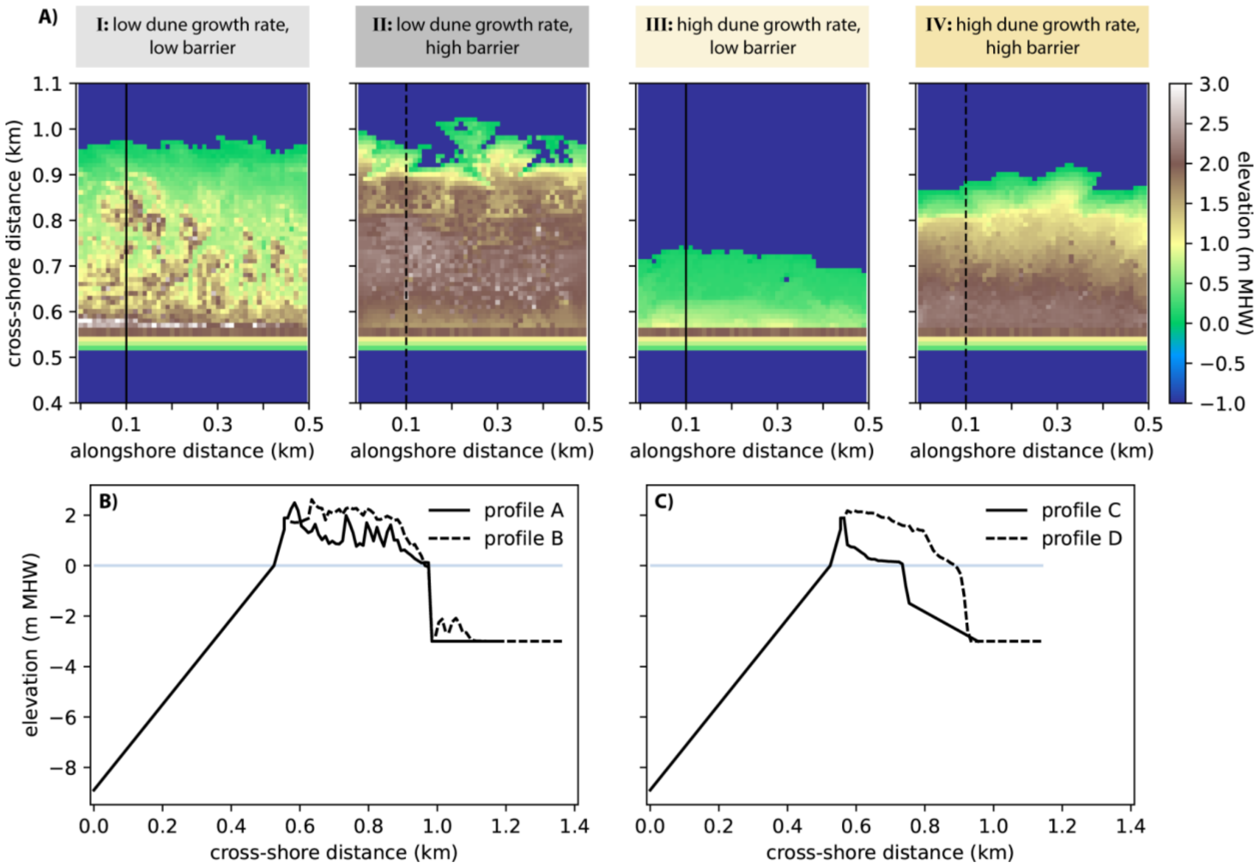

Figure 2. Initial barrier configurations for the management simulations (referenced as configurations I-IV herein) in **a)** planform and **b-c)** sample cross-sectional view (at 0.1 km). A low barrier elevation profile (solid line) and high barrier elevation profile (dashed line) illustrate elevation differences.

2.3 Initial conditions

We initialize Barrier3D (within CASCADE) using the default conditions described by Reeves et al., (2021), which are parameterized for Hog Island, Virginia, USA: a low-lying and undeveloped barrier island in the Virginia Coastal Reserve. We choose this location because there is a wealth of information on natural dune and barrier dynamics (as opposed to more developed regions along the NC coast). Under default conditions, the dune field is 20 m (or 2 cells) wide, the natural equilibrium dune crest elevation is 3.4 m NAVD88, the berm elevation is 1.9 m NAVD88, the MHW line is 0.46 m NAVD88, and the bay depth is 3 m. In Barrier3D, and herein, all elevations are relative to the MHW datum.

We utilize the same 10,000 synthetic storms as Reeves et al., (2021), which were developed using the multivariate sea-storm model of Wahl et al., (2016) and derived from a 35-yr empirical storm record for Hog Island (Reeves et al., 2022). Each storm is defined by three variables: the maximum runup elevation, the minimum runup elevation, and duration. This list of multivariate storms is then used to generate stochastic storm sequences, here with a specified average of eight storms per year (in accordance with the historical data record used to generate the synthetic storms: 242 storms over 33 years). In CASCADE, the default shoreface geometry from Barrier3D is modified to match that in BRIE. For this purpose, we specify a deepwater wave height of 1 m and a 7-sec wave period. The fraction of waves approaching from the left (looking offshore) is set to 0.8 and the fraction of high angle waves (e.g., Ashton and Murray, 2006) is 0.2. The remaining initial conditions in BRIE are set to the default values (Table 1 in Nienhuis & Lorenzo-Trueba, 2019a). This results in a shoreface depth of 8.9 m, shoreface flux constant of ~19,000 m^3/m/yr, and an equilibrium shoreface slope of 0.017. A full list of initial conditions for each CASCADE simulation is provided in the Supplement (Table S1).

In Barrier3D, (natural) barrier evolution is influenced by the characteristic dune growth rate $\underline{r}$ (Houser et al., 2015; Durán & Moore, 2013), as well as exogenous factors including the rate of SLR, storm frequency, and storm intensity (Reeves et al., 2021). The model produces autogenic variability in barrier elevation and width over decadal timescales. The range of this variability is particularly sensitive to dune growth rate, with low dune growth rates showing limited autogenic variability (steady state characterized by a high barrier interior elevation and wide barrier) and high dune growth rates showing greater autogenic variability (typically exhibiting a state characterized by a lower barrier interior elevation and narrower barrier width; see Figure S3).

Given that the timing of initial development and management of barrier systems within this autogenic variability in barrier geometry likely has implications for pathways toward uninhabitability, we initialize the management simulations that follow with four different topographies extracted from 10,000-year simulations of natural barrier evolution (see Supplement). These topographies consist of a high barrier elevation state and a low barrier elevation state for each dune growth rate (low and high). The four resulting initial barrier configurations used in our management simulations are shown in Figure 2a-d and are herein referred to as configurations I-IV. We also simulate natural barrier evolution for each initial barrier configuration to identify modifications to natural barrier dynamics arising from management strategies (i.e., there are four natural baseline scenarios; Table 1). All configurations are initialized with the same dune line, with dune heights ranging from 0.4 to 0.6 m.

The model is capable of producing the differential effects of linear versus accelerated SLR. Because all four initial barrier configurations can naturally keep pace when SLR is linear at 4 mm/yr (Figure S4), we first use this rate to examine how roadway barrier- and community barrier-management actions in isolation change the physical characteristics of barrier systems over long time scales. We then explore more complex scenarios under both linear and accelerated SLR. Our linear SLR scenario extends for 1000 years, but due to the challenges of extending accelerated rates into the distant future, accelerated SLR scenarios are capped at 200 years. As discussed in the Supplement, our scenario of accelerated SLR results in a cumulative increase in sea level of 0.65 m after 100 years and 2.3 m after 200 years, which is within the bounds of projected SLR for RCP4.5 by 2100 and RCP8.5 by 2200 (medium and low confidence, respectively; Oppenheimer et al., 2019).

3 Results

Model results are presented in order of increasing management complexity, beginning with management of a single roadway on a barrier segment and ending with alongshore variability in roadway barrier-management and community barrier-management strategies amidst alongshore differences in barrier configuration. Each management scenario and its associated model simulations are summarized in Table 1. In the results that follow, an ‘uninhabitable state’ occurs when roadway barrier management and/or community barrier management cease in our simulations – that is, when the barrier interior is too low (i.e., 20% of the roadway touches water cells) or the island is too narrow (<40-m wide) to relocate the roadway, or when the barrier is too narrow (i.e., <50-m wide) to accommodate the combined footprint of a home and a roadway required to sustain a community.

Table 1. Model simulation parameters for each natural and management scenario. For simulations with multiple barrier segments that are initialized with more than one barrier configuration, initial configurations used are separated by '&.' For example, the status quo scenarios simulate a barrier system with three commercial segments (initialized with configuration III) connected in the alongshore to six roadway segments (three initialized with configuration I and three initialized with configuration III) denoted as III & I & III. The increased alongshore complexity scenarios denoted with (*) are simulated for an additional 100 storm sequences (see Table 2).

Scenarios	# of model simulations	Initial barrier configuration	# of barrier segments	SLR	Background erosion rate	Relevant figures
Natural scenario (Section 3.1-3.2)						
baseline scenario	4	I, II, III, IV	1 natural	linear	0 m/yr	3-6
Roadway barrier-management scenarios (Section 3.1)						
1-m design height	4	I, II, III, IV	1 roadway	linear	0 m/yr	3, 4
2-m design height	4	I, II, III, IV	1 roadway	linear	0 m/yr	3, 4
3-m design height	4	I, II, III, IV	1 roadway	linear	0 m/yr	3, 4
2-m design height + back. erosion (baseline road)	1	III	6 roadway	linear	1 m/yr	9
Community barrier-management scenarios (Section 3.2)						
residential overwash filtering	4	I, II, III, IV	1 residential	linear	0 m/yr	5, 6
commercial overwash filtering	4	I, II, III, IV	1 commercial	linear	0 m/yr	5, 6
commercial overwash filtering + back. erosion	4	I, II, III, IV	1 commercial	linear	1 m/yr	5, 6
commercial overwash filtering + back. erosion (baseline community)	2	I, III	6 commercial	linear	1 m/yr	9
Roadway + community barrier-management scenarios (Section 3.3)						
alongshore-uniform initial configuration, linear SLR	1	III	3 commercial, 3 roadway	linear	1 m/yr	7, 9
alongshore-uniform initial configuration, accelerated SLR	1	III		acc.	1 m/yr	7, 9
alongshore-varying initial configuration, linear SLR	1	III & I		linear	1 m/yr	8, 9
alongshore-varying initial configuration, accelerated SLR	1	III & I		acc.	1 m/yr	8, 9, 12
Increased alongshore complexity scenarios (Section 3.4)						
status quo, linear SLR	1	III & I & III	3 commercial, 3 roadway, 3 roadway	linear	1 m/yr	10
status quo, accelerated SLR	1*	III & I & III		acc.	1 m/yr	10, 12
preemptive road removal	1*	III & I & III		acc.	1 m/yr	11, 12
status quo, accelerated SLR, increased storminess	100	III & I & III		acc.	1 m/yr	Table 2
preemptive road removal, increased storminess	100	III & I & III		acc.	1 m/yr	Table 2

3.1 Roadway barrier-management scenarios

The time evolution of barrier and dune dynamics in response to roadway management is shown in Figures 3 and 4, respectively. In Figure 3, we identify modifications to natural barrier dynamics arising from the three different roadway barrier-management scenarios (Table 1) by comparing barrier geometry (here, average elevation and width), shoreline retreat, and overwash flux for each management scenario for each of the four initial barrier configurations (I-IV), with the corresponding natural baseline simulation. Roadway barrier-management scenarios differ only in the dune design height (1, 2, and 3 m above the roadway). In Figure 4, we evaluate differences in dune elevation between the managed and natural dune scenarios relative to the dune rebuild threshold, the roadway elevation, and the natural equilibrium dune crest elevation.

In all cases, roadway barrier management results in a narrowing and lowering of barriers relative to natural conditions, a consequence of limiting overwash by maintaining artificial dunes. With artificially tall dunes, the barrier interior does not receive enough sediment to keep pace with SLR and, over the timescale of decades, the barrier narrows as SLR progressively floods the relatively lowering interior. The tallest dune design height (3 m) limits the most overwash and therefore leads to more rapid roadway abandonment (4 to 211 years earlier than the 2-m dune design-height scenario; dashed lines in Figure 3). Lower dune design heights (1 and 2 m above the roadway) are more frequently overtopped and allow for some overwash to reach the barrier interior, increasing barrier elevation and width. However, more overwash also causes faster shoreline retreat, potentially leading to island migration. Overall, lower dunes trigger more frequent use of dune and roadway management strategies: more frequent overwash leads to more frequent overwash removal from roadways and rebuilding of dunes, whereas faster shoreline retreat leads to more frequent road relocation. Road relocations appear in Figure 4 as sharp (step) changes in the road elevation. For example, in the case of a low dune growth rate and initially high barrier (configuration II), the road is relocated seven, five, and three times when the dune is rebuilt to a 1-m, 2-m, and 3-m dune design height, respectively. Similarly, the dune is rebuilt 21 times for a 1-m dune design height (62% due to shoreline retreat), 10 times for a 2-m dune design height (90% due to shoreline retreat), and five times for a 3-m dune design height (100% due to shoreline retreat).

The length of time over which roadway barrier management occurs varies primarily as a function of the initial geometry of the barrier (e.g., lower and narrower as in configuration III, versus higher and wider, as in configurations II and IV), and secondarily as a function of the dune design height. For the lowest and narrowest initial barrier configuration (III: high dune growth rate, low initial barrier) and tallest dune design height (3 m), the roadway is abandoned after 131 years, whereas for the same dune design height and a higher and wider initial barrier configuration (II: low dune growth rate, high barrier), the road is abandoned after 522 years (Figure 3). This represents an approximately 400-year difference in the period of time over which roadway barrier management occurs. For all but the lowest and narrowest of the initial barrier configurations (III: high dune growth rate, low initial barrier), dune design height also affects the length of the roadway management time period. For example, for a 1-m dune design height and a higher and wider initial barrier (II: low dune growth rate, high initial barrier), the roadway can be managed for an additional 128 years beyond the 3-m dune design-height scenario.

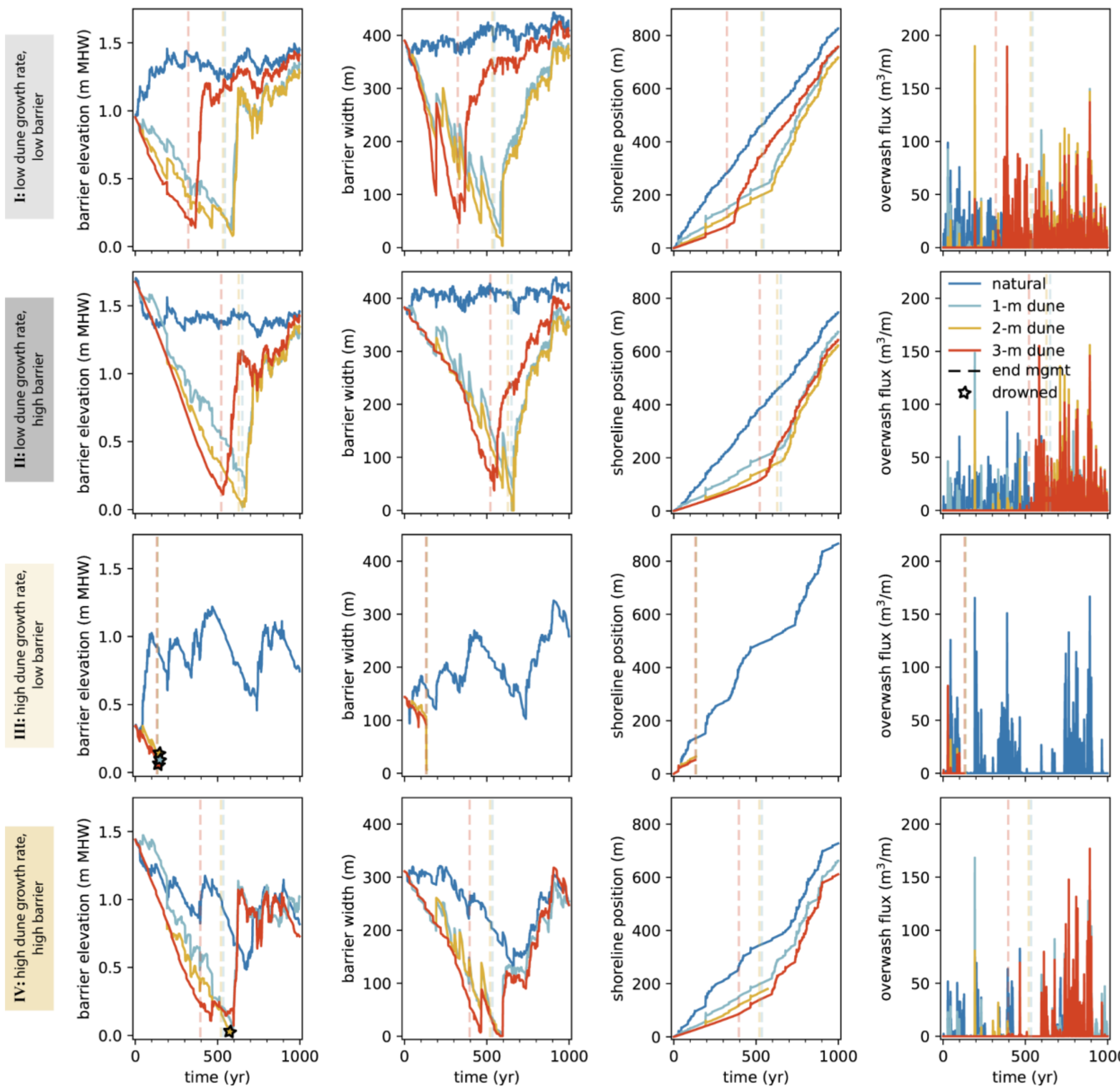

Figure 3. Time evolution of average barrier elevation, average barrier width, shoreline position, and overwash flux (columns) for each roadway barrier-management scenario (dune design heights of 1, 2, and 3 m above the roadway; colors) and initial barrier configuration (rows) with linear SLR (4 mm/yr). Vertical dashed lines delineate when roadway management ceased for each dune design height; stars indicate barrier drowning after management ceased.

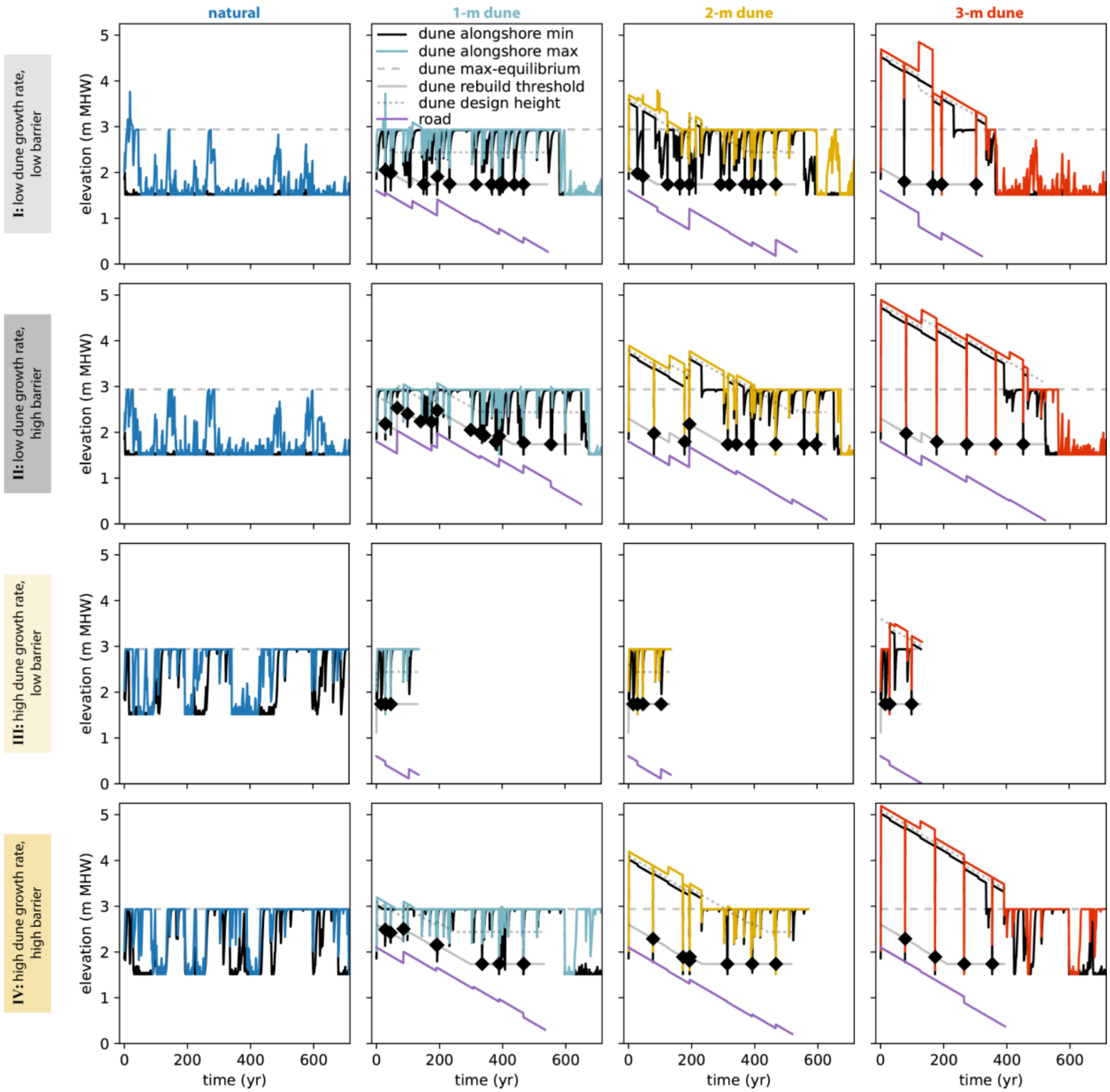

Figure 4. Dune and road elevations over time for each roadway barrier-management scenario (columns, colors) and initial barrier configuration (rows). Dunes are rebuilt when their crest elevation falls below the rebuild threshold (solid gray line), which is relative to the roadway elevation (purple line) and therefore reduced by SLR at each time step. Natural dune growth does not occur when the elevation of the rebuilt dune cell is higher than the natural equilibrium dune crest elevation (dashed gray line). Diamonds indicate when the dunes are rebuilt in response to shoreline retreat (versus dune lowering from storms). Only the first 700 years of each 1000-year simulation are shown for clarity of presentation.

After management ceases, whether a barrier drowns or is ultimately able to rebound depends on dune-storm stochasticity – that is, stochasticity in the timing of a storm of sufficient intensity to overtop the dune while it is still recovering from a previous storm. For all scenarios, the roadway is abandoned while dunes are in a high state – that is, at or above the natural equilibrium crest elevation. For the three scenarios that result in barrier drowning (depicted by stars in Figure 3), no storm of sufficient intensity to overtop the dunes occurred after management ceased and therefore the barrier continued to become narrower and lower until the interior became submerged. For barriers that do not drown after management ceases, dune-storm stochasticity, and the rate of dune recovery (slower in the case of low dune growth rate and faster in the case of high dune growth rate) dictate how quickly the barrier can recover in elevation, width, and cross-shore position. For several scenarios, a sequence of large storms results in rapid rebuilding of barrier elevation and width following roadway abandonment (e.g., 28 years for the 3-m dune design height and configuration IV (high dune growth rate, high initial barrier) and a return toward the decadal autogenic variability of the natural baseline simulations.

3.2 Community barrier-management scenarios

The same outputs presented above are shown in Figures 5 and 6 for three community barrier-management scenarios (simulated for each initial barrier configuration, I-IV; Table 1). The first two community management scenarios differ from each other in that they include the filtering effect of residential and commercial development on overwash placement, respectively. The third scenario includes the filtering effect of commercial development as well as 1 m/yr of background erosion to account for chronic shoreline retreat driven by processes other than SLR (i.e., alongshore sediment transport gradients arising from shoreline curvature; Slott et al., 2006). All three scenarios include beach nourishment and maintenance of artificial dunes to hold shoreline and dune positions in place (i.e., a minimum beach width of 30 m and dune design height of 2 m above the average initial barrier elevation).

Despite the added complexity of differential overwash filtering arising from the representation of residential versus commercial development, dune dynamics play the same role in barrier evolution in these simulations as they do in the roadway simulations: managed dunes prevent overwash from occurring, which leads to narrowing and lowering of barrier segments (Figure 5). Although overwash is greatly limited by dune management, when it does occur in our simulations, residential development enables more overwash to be placed on the island interior (as compared to commercial properties), prolonging the timing to abandonment by 32 to 115 years depending on the initial configuration of the barrier. When compared to the four simulations for the roadway barrier-management scenario with a 2-m dune design height, which is most similar to the community barrier-management scenarios, the filtering effect of residential and commercial properties on overwash placement leads to more rapid lowering and narrowing of barriers that have low dune growth rates. In these cases, community abandonment occurs 84 to 231 years earlier than in the comparable roadway simulation. For barriers with high dune growth rates, the timing of abandonment is similar between the community and roadway simulations. For the lowest and narrowest initial barrier configuration (III: high dune growth rate, low initial barrier), the community is abandoned after only 83 years when managed for commercial properties and 160 years when managed for residential properties – which is earlier and later, respectively, than roadway abandonment in the comparable roadway simulation (135 years; Figure 3).

We find that the average frequency of beach nourishment required to maintain shoreline (and therefore community) position is always higher for communities with residential versus commercial properties because residential properties allow more overwash to reach the island interior, and therefore result in greater shoreline retreat. For example, for the low dune growth rate, low initial barrier configuration (configuration I), over the first 200 years of the simulation, the residential community nourishes every 33 years on average whereas the commercial community nourishes every 40 years on average (Figure 5). With the addition of background erosion, the frequency of nourishment needed to counter shoreline retreat increases nearly fourfold to an average interval of nine years (for comparison, the largest nourishments in Nags Head, NC occurred in 2011 and 2019 – a separation of eight years).

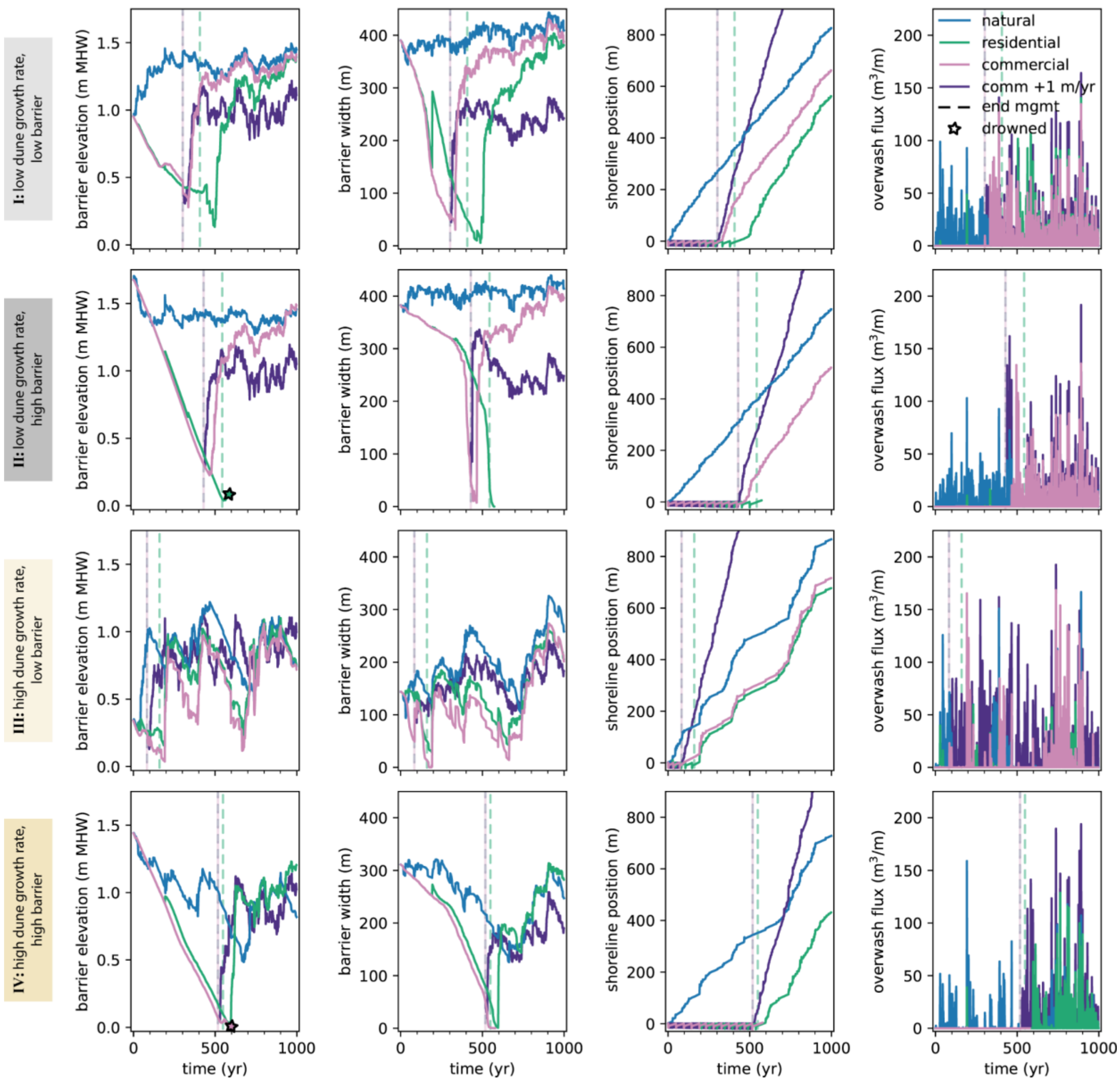

Figure 5. Time evolution of average barrier elevation, average barrier width, shoreline position, and overwash flux (columns) for each community barrier-management scenario (colors) and initial barrier configuration (rows) with linear SLR (4 mm/yr). Scenarios include dune and beach management for a community with residential properties (overwash filtered by 40%), commercial properties (overwash filtered by 90%), and management for commercial properties with an added background erosion of 1 m/yr. Dashed lines delineate when management ceased; stars indicate barrier drowning after management ceased.

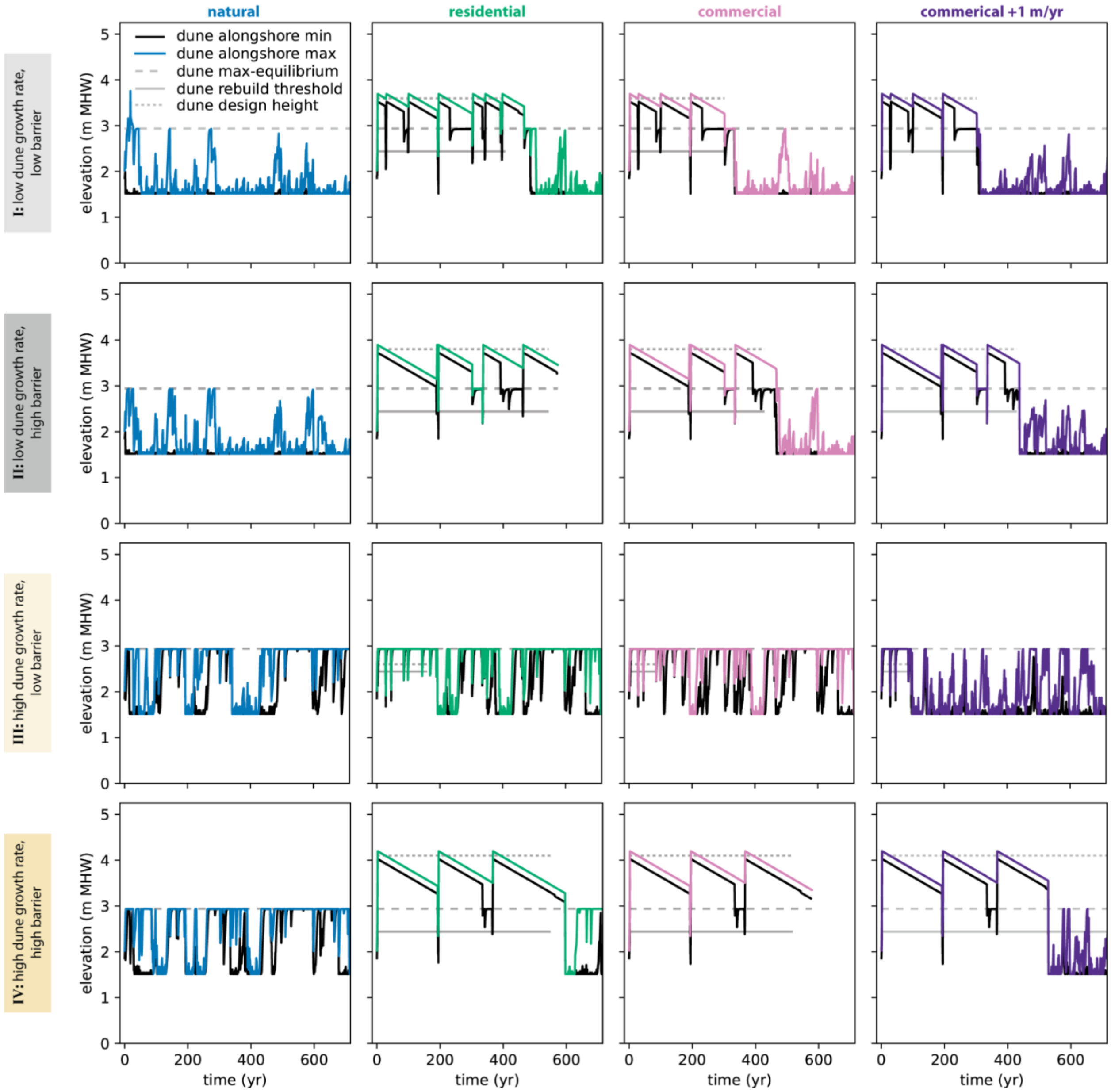

Figure 6. Dune elevation over time for each community barrier-management scenario (columns) and initial barrier configuration (rows). Dunes are rebuilt when their elevation falls below the dune rebuild threshold (solid gray line), which is fixed at 1 m above the berm elevation (1.44 m MHW) for the duration of management. This provides oceanfront homes with consistent dune protection. Dunes are rebuilt to a set elevation (i.e., a dune design height of 2 m above the initial average barrier elevation), which for most scenarios is above the natural equilibrium dune elevation (dashed gray line).

Background erosion also influences barrier drowning. While dune-storm stochasticity still dictates whether or not a barrier drowns in the community barrier-management simulations, for the high dune growth rate, high initial barrier configuration (configuration IV), the addition of background erosion leads to rapid erosion of the dune line after abandonment (at 529 years, approximately ten years after community abandonment; Figure 6). This allows the barrier to be quickly overwashed, which builds island elevation and increases island width (as compared to the commercial scenario without background erosion, where dunes remain high after the community is abandoned at 518 years and thereafter the barrier drowns at 580 years). Note that because the natural scenario does not include background erosion (Figures 5-6), it cannot be directly compared to the commercial scenario with background erosion. For the residential and commercial scenarios that show barrier rebound after abandonment (and do not include background erosion), the barriers tend to evolve toward the autogenic variability in barrier elevation, island width, and shoreline position by the end of the 1000-year simulations, approaching the autogenic variability of the natural steady state.

3.3 Roadway+community barrier-management scenarios

In the previous sections, management strategies to maintain a roadway and community were simulated separately for a single barrier segment. Here, we describe the results of four scenarios (one simulation each, Table 1) in which we connect – via alongshore sediment transport – barrier segments with different management strategies and explore how evolutionary trends differ with alongshore connectivity. In all four of the roadway+community barrier-management scenarios described in the text that follows, three 0.5-km segments are managed to protect commercial properties (community segments) and three additional adjacent 0.5-km segments are managed to protect roadways (roadway segments, 2-m dune design height), for a total domain length of 3 km. The first two scenarios – the "alongshore-uniform initial configuration" scenarios – have the same initial barrier configuration in the community and roadway segments and are run for linear SLR and accelerated SLR, respectively (Figure 7). Because natural barriers exhibit alongshore variations in elevation and width, two additional scenarios – the "alongshore-variable initial configuration" scenarios – have a different initial barrier configuration in the community segments than in the roadway segments and are run for linear SLR and accelerated SLR (Figure 8).

For simplicity, we do not attempt to connect the barrier interior or bay cells of individual barrier segments via sediment exchange, which would likely result in only small changes to the barrier morphology. All four simulations include a background erosion rate of 1 m/yr and run for 200 years for consistency, given that this is the length limit for simulations using accelerated SLR. To best simulate large-scale (several km) nourishment practices, nourishment is triggered when the beach width in all community segments falls below the beach width threshold of 30 m. Because a roadway must be continuous to be functional, we consider all adjacent roadways across multiple barrier segments to be abandoned once roadway abandonment occurs in any one segment.

3.3.1 *Alongshore-uniform initial configuration scenarios*

For the alongshore-uniform initial configuration scenarios, all barrier segments are initialized with the lowest and narrowest initial barrier configuration (III: high dune growth rate, low initial barrier; Figure 7). In these scenarios, abandonment of the community occurs before abandonment of the roadway because the community segments are relatively more overwash-starved than the roadway segments. Under linear SLR (4 mm/yr; Figure 7a-c), the community is abandoned after 83 years of management; thereafter, a storm of sufficient intensity overtops the remnant dune and the barrier is overwashed. The roadway continues to be managed until 143 years; after roadway abandonment, the barrier is quickly overwashed, which allows the entire 3-

km barrier system to transgress landward. For the case of accelerated SLR (Figure 7d,e), community abandonment (at 64 years) precedes roadway abandonment, however, the barrier drowns at 85 years while the roadway is still being managed (the timestep before drowning is shown in Figure 7e). Although it may seem unnecessary to maintain a roadway after a community has been abandoned, we assume here that access to the island is still desirable.

3.3.2 *Alongshore-variable initial configuration scenarios*

In the alongshore-variable initial configuration scenarios, the community (commercial) segments are initialized with a slightly higher and wider initial barrier configuration (I: low dune growth rate, low initial barrier) than the roadway segments (same as in the alongshore-uniform initial configuration scenarios above; III: high dune growth rate, low initial barrier). The roadway is abandoned prior to the community in both cases, at 131 years and 85 years for the linear (Figure 8a,b) and accelerated SLR scenarios (Figure 8c-e), respectively. Under linear SLR, the community is not abandoned prior to the end of the 200-year run. Consequently, the shoreline along the community segments remains fixed through the end of the simulation whereas the shoreline along the roadway segments moves landward due to overwash, resulting in an offset in shoreline position between the community and barrier segments (Figure 8b). Under accelerated SLR, the community is abandoned at 137 years and soon after the barrier drowns (at 141 years; the timestep before drowning is shown in Figure 8e). The shoreline at drowning is nearly straight because the community segments transgress quickly after abandonment, approaching the shoreline position of the roadway segments.

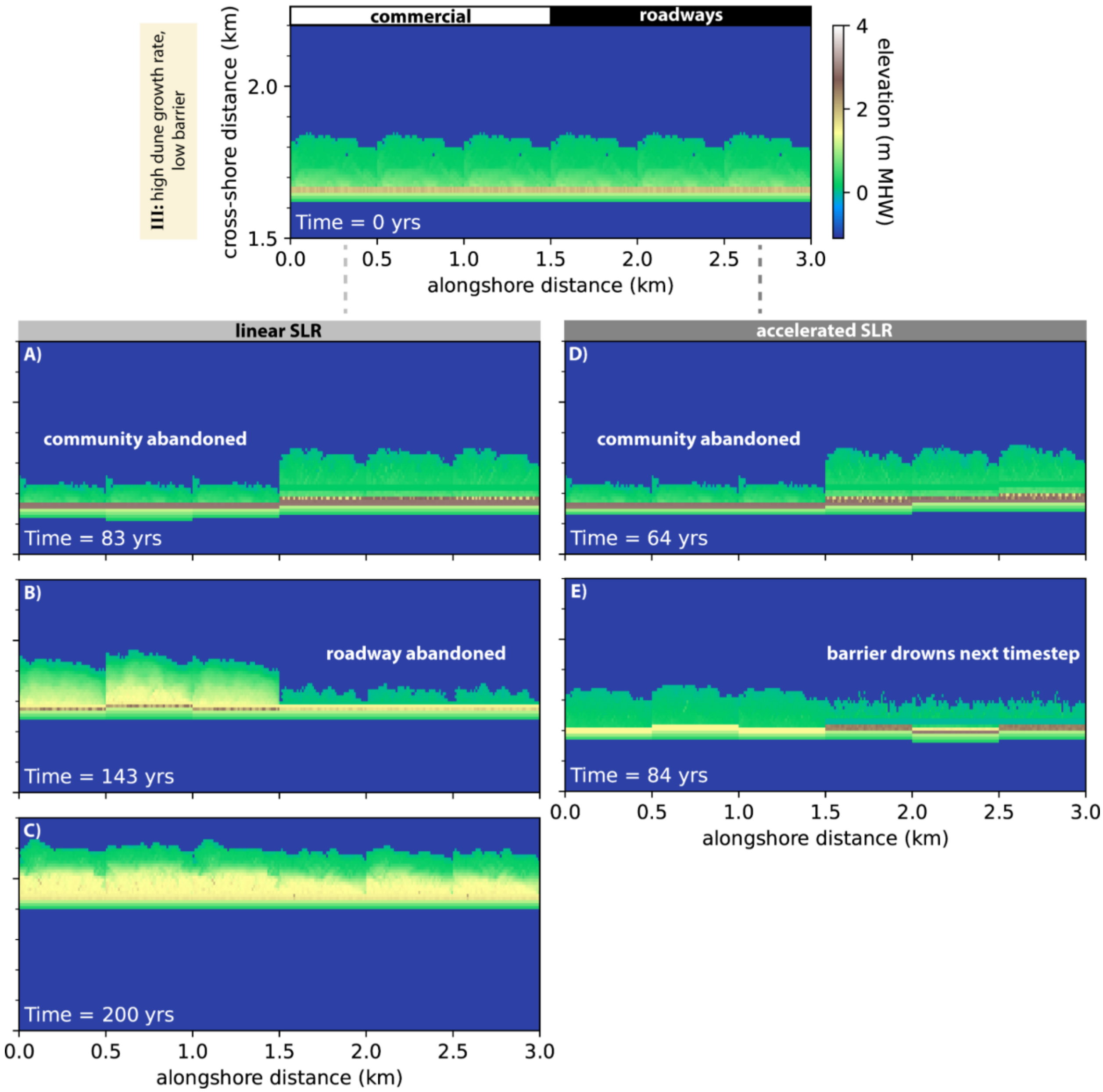

Figure 7. Planform evolution of the roadway+community barrier-management, alongshore-uniform initial configuration scenarios for **a-c**) linear SLR (4 mm/yr) and **d-e**) accelerated SLR, where a low and narrow barrier system is managed for a community on the left half of the domain (0-1.5 km) and managed for a roadway on the right half (1.5-3 km), with 1m/yr of background erosion. Panels **a)** and **d)** correspond to the timing of community abandonment, and **b)** roadway abandonment. Panel **c)** is the final simulation state (linear SLR). For the case of accelerated SLR, the barrier drowns at 85 years, while the roadway is still being managed (the timestep before drowning is shown in **e**).

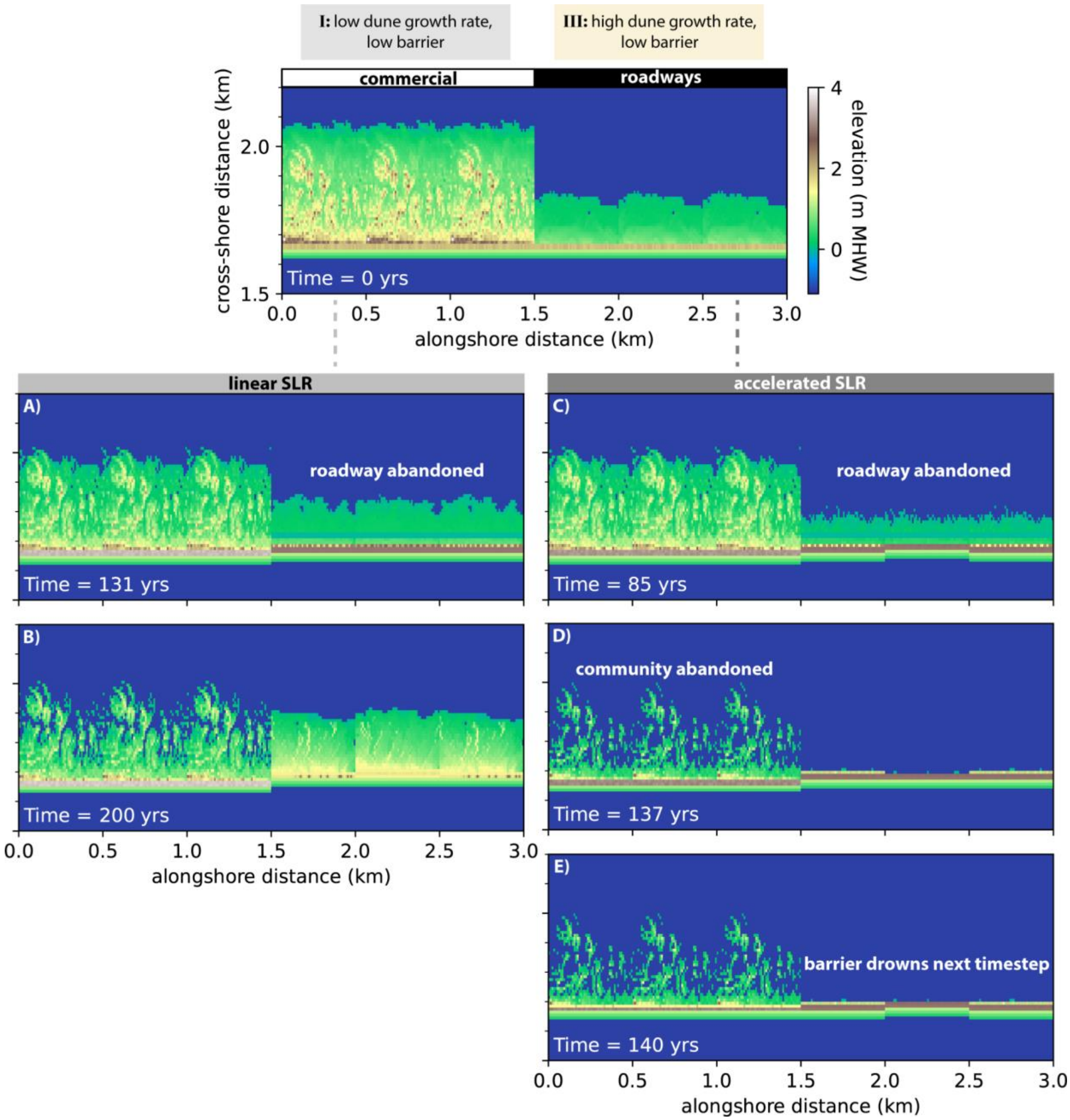

Figure 8. Planform evolution of the roadway+community barrier-management, alongshore-varying initial configuration scenarios for **a-b**) linear SLR (4 mm/yr) and **c-e**) accelerated SLR, where a higher and wider barrier system is managed for a community on the left half of the domain (0-1.5 km) and a lower and narrower barrier system is managed for a roadway on the right half (1.5-3 km), with 1 m/yr of background erosion. Panels **a)** and **c)** correspond to the timing of roadway abandonment, and **d)** community abandonment. Panel **b)** is the final simulation state (linear SLR). For the case of accelerated SLR, the barrier drowns at 141 years (the timestep before drowning is shown in **e**).

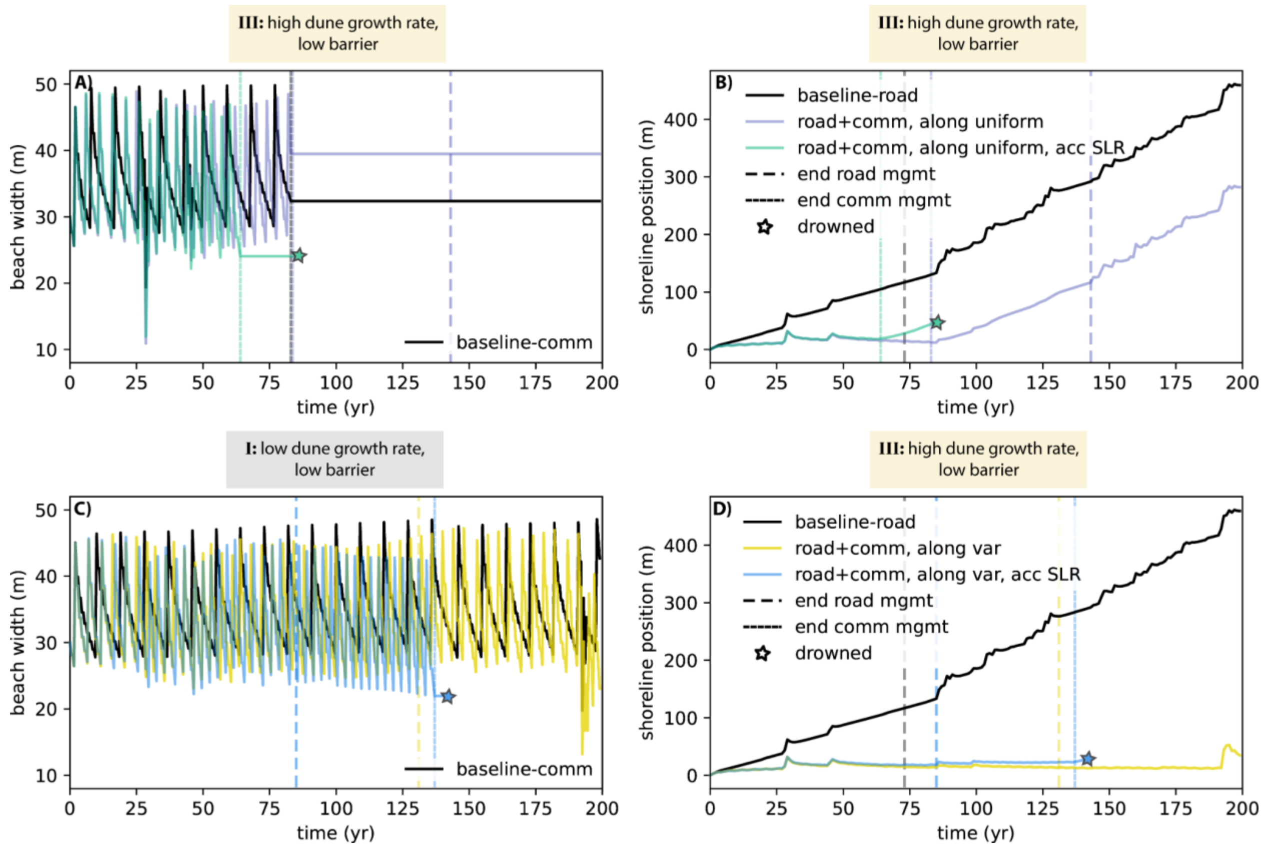

Figure 9. Time evolution of beach width and shoreline position for the middle barrier segment in the community (**a,c**: 0.5-1 km) and roadway management blocks (**b,d**: 2-2.5 km) from the roadway+community management scenarios for **a-b**) linear SLR and **c-d**) accelerated SLR (as shown in Figure 7a,b and Figure 8c,d for the alongshore-uniform and alongshore-variable initial configuration scenarios, respectively). The roadway+community barrier-management scenarios are compared to baseline community and baseline roadway simulations (see Table 1) with no alongshore variability in management or initial barrier configuration (all 3-km long), background erosion of 1 m/yr, and with linear SLR (4 mm/yr; black lines). The fine (coarse) dashed vertical lines delineate when community (roadway) barrier management ceased for each simulation; stars indicate barrier drowning.

3.3.3 *Comparison of roadway+community barrier-management scenarios*

Comparing the time evolution of beach width and shoreline position for each of the four roadway+community barrier-management scenarios for the middle barrier segment in the community and roadway management blocks (0.5-1 km and 2-2.5 km, respectively) allows for more detailed examination of what happens to adjacent barrier segments after part of the barrier system has been abandoned (Figure 9a-b relates to Figure 7 and Figure 9c-d relates to Figure 8). The black lines in Figure 9 correspond to a 3-km simulation with no alongshore variability in management and linear SLR (i.e., the corresponding "baseline" community or roadway barrier-management scenario for each initial barrier configuration; see Table 1).

In Figure 9b, after the community is abandoned (fine dashed vertical lines) and subsequently overwashed, the shoreline along the roadway segments transgresses landward in both SLR scenarios, "pulled" by the transgression of the overwashed neighboring segments through gradients in alongshore transport that diffuse shoreline position. Prior to this time, shoreline position in the roadway segments was stabilized at a fixed cross-shore position, maintained by sediment lost from the neighboring community following each nourishment. This “suckers and freeriders” effect (Williams et al., 2013) forces the community to nourish more frequently than it would have if roadway barrier management had not been occurring in the other half of the domain (comparison between colored lines and the dashed black line in Figure 9a).

Similarly, for the case shown in Figure 9c – when the roadway is abandoned prior to the community (coarse dashed vertical lines) – the community continues to maintain its fixed cross-shore position through nourishment, inadvertently stabilizing the adjacent shoreline of the abandoned roadway (Figure 9d). In the case of linear SLR, nourishment frequency remains constant until 193 years (average interval = 4 years); thereafter, two large storms move the abandoned roadway segments approximately 40 m landward (Figure 9d), which results in a need for more nourishment to maintain the specified 30-m beach width in front of the community (Figure 9c). For scenarios with accelerated SLR, the frequency of beach nourishment increases through time to keep pace with sea level.

3.4 Increased alongshore complexity scenarios

To explore the effect of further increases in alongshore complexity, we add three more barrier segments, all managed for roadways, to the right side of the domain used in the alongshore varying initial-configuration scenarios shown in Figure 8. The resulting increased alongshore complexity scenarios introduced below are motivated by the town of Rodanthe, NC, USA, which was developed in the 1930s as a fishing community and is bordered to the north by a wildlife refuge containing a single roadway (NC-12). A 3-km segment of this roadway, just north of Rodanthe, was abandoned in July 2022 due to frequent overwash and an inability to relocate the road landward because the barrier is too narrow locally. The abandoned road segment was replaced with a back-barrier bridge that bypasses the vulnerable barrier segments (NCDOT, 2022).

In our simulations, the low and narrow middle three segments of the barrier system are managed for a roadway and bracketed by three wider and higher barrier segments on the left that are managed to protect a community (commercial) and three wider and higher barrier segments on the right that are managed to protect a roadway (2-m dune design height). We run simulations for linear SLR (Figure 10a-b) and accelerated SLR (Figure 10c) and refer to these two scenarios as the “status quo” scenarios because we assume (as before) that community and roadway managers will continue to manage the barrier until it becomes untenable for development – that is, they will ‘hold the line’ of oceanfront homes or relocate the roadway until the barrier narrows and lowers to the critical threshold.

In a final scenario, we examine the effects of a potential climate adaptation measure: preemptive abandonment of management practices long before the barrier is deemed uninhabitable for a community or unable to support a roadway. Specifically, we explore in Figure 11 how the barrier system modeled in the status quo scenarios evolves under accelerated SLR if the barrier segments in the middle of the domain are allowed to evolve naturally, without management. This scenario is analogous to partial abandonment of a roadway before it is deemed untenable and is herein referred to as the “preemptive road removal” scenario. We conclude with an investigation of the effects of enhanced storminess for all three of the increased alongshore complexity scenarios.

3.4.1 *Status quo scenarios*

Comparing the planform evolution of the barriers in the alongshore-variable initial configuration scenarios (Figure 8) and status quo scenarios (Figure 10) reveals that the addition of three more roadway segments on the right side of the domain results in several dynamical changes in barrier evolution. First, the low (middle) roadway segments migrate landward faster in the status quo scenarios (1.5-3 km) than the low roadway segments in the alongshore-variable initial configuration scenarios (1.5-3 km). The explanation for this involves the periodic boundary conditions in CASCADE, which for the alongshore-variable initial configuration scenarios means the roadway section is implicitly bounded on both sides by barrier segments that are managed to protect a community. Given that shoreline position is fixed in the community segment, the roadway segments are limited in how far they can migrate landward because gradients in alongshore sediment transport tend to maintain a smooth shoreline of limited curvature. In contrast, in the status quo scenarios there are two sets of segments managed to protect a roadway between two sets of community segments (the one shown on the left side of the domain and the one that is implicit beyond the right side of the domain). The greater distance between stabilized shoreline segments allows the shoreline in the middle roadway section (1.5-3 km) to migrate farther landward relative to the alongshore-variable initial configuration scenarios. This finding is shown in more detail in the time series of shoreline position (for the cases of accelerated SLR) in Figure 12b.

In addition to the contrasting shoreline erosion rates, the roadway is abandoned somewhat earlier in the status quo scenario with linear SLR (99 years, Figure 10a) as compared to the alongshore-variable initial configuration scenario (131 years, Figure 8a). This is because the higher shoreline retreat rates in the low (middle) roadway section in the status quo scenario relative to the roadway section in the alongshore-variable initial configuration scenario remove the part of the barrier that was initially highest, just landward of the initial dune location. Dunes are also eroded more rapidly because of the retreating shoreline and therefore are rebuilt earlier in the status quo scenario. Higher dunes could ultimately result in less overwash delivery but given the absence of significant overwash deposition in either scenario, removing the initially highest part of the barrier is the principal factor that causes earlier barrier drowning in the status quo scenario.

Greater alongshore variability in overwash fluxes in the status quo scenarios also creates complex coastline shapes: because the community remains in a fixed cross-shore position, the landward migration of the roadway segments (1.5-4.5 km) creates curvature in the coastline to the right of the community in both SLR scenarios (Figure 10b-c). Under accelerated SLR, the middle barrier segments drown at 71 years while the roadway is still being managed. This drowning occurs 70 years earlier than in the alongshore-variable initial configuration scenario with accelerated SLR (Figure 8c-e), representing a factor of 2 decrease.

Lastly, the average nourishment frequency is slightly higher for the community in the status quo scenarios than in the alongshore-variable initial configuration scenarios. For example, with accelerated SLR, the average nourishment interval prior to roadway abandonment for the alongshore-variable initial configuration scenario is 3.7 years, versus 3.4 years in the status quo scenario (averaged over the same time period; Figure 12a). This occurs because with twice the length of roadway segments in the domain, more sediment is lost alongshore (as in Slott et al., 2008).

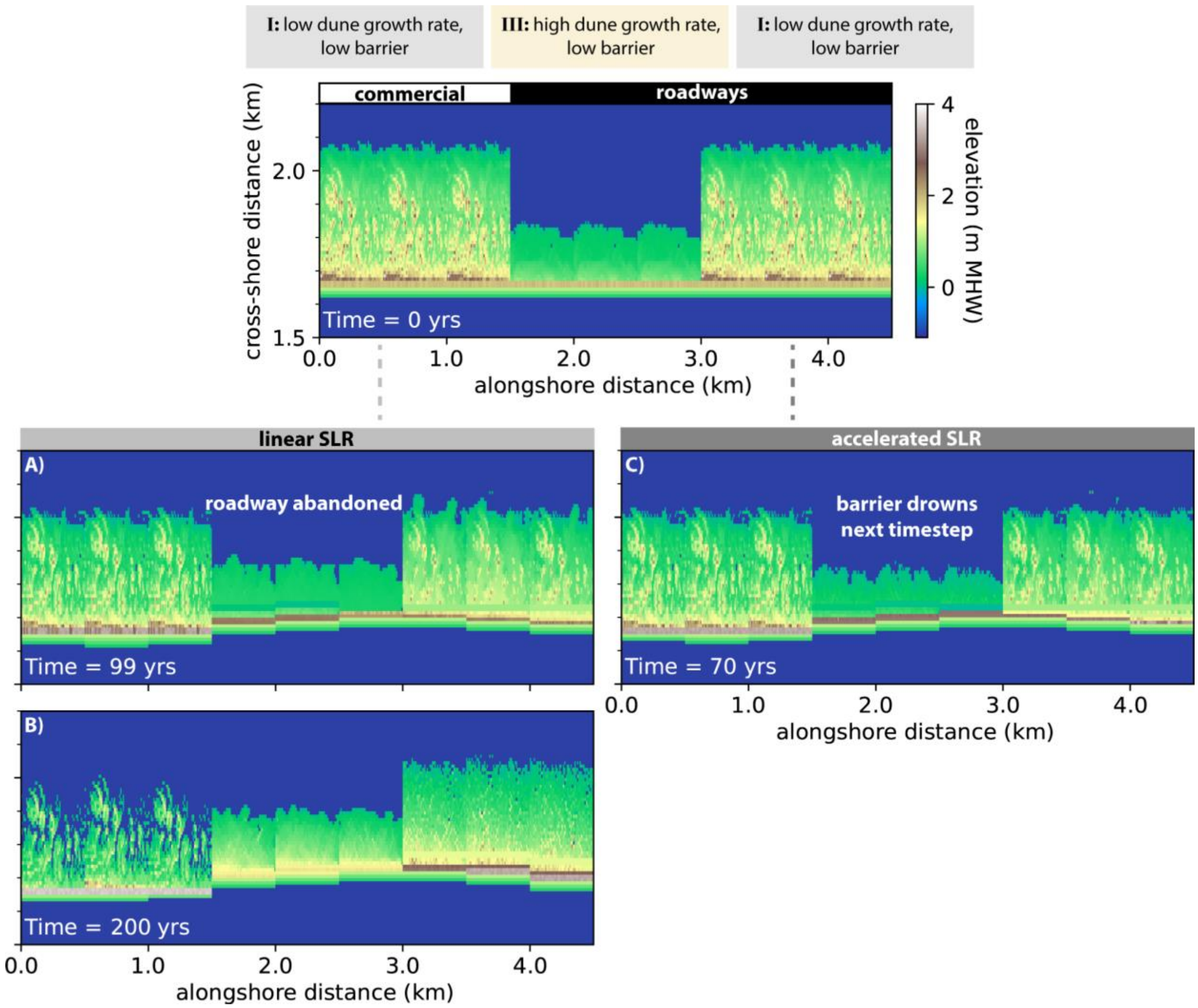

Figure 10. Planform evolution of the increased alongshore complexity, status quo scenarios for **a-b**) linear SLR (4 mm/yr) and **c**) accelerated SLR, where three additional barrier segments (3-4.5 km), all managed for roadways (2-m dune design height), are added to the right side of the domain used in the roadway+community management, alongshore-variable initial configuration scenarios, with 1 m/yr of background erosion. Panel **a)** corresponds to the timing of roadway abandonment in the middle 3-segments of the domain (1.5-3 km) and panel **b)** is the final simulation state. For the case of accelerated SLR, the barrier drowns at 71 years, while the roadway is still being managed (the timestep before drowning is shown in **c**).

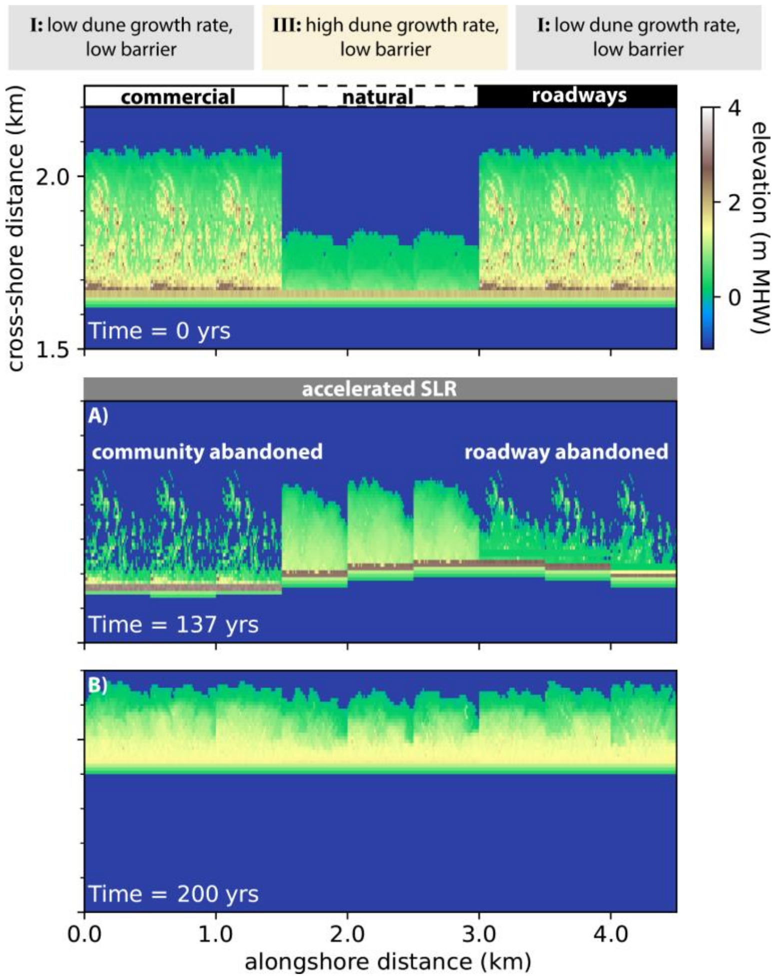

Figure 11. Planform evolution of the increased alongshore complexity, preemptive road removal scenario where the most low-lying and narrow barrier segment is allowed to evolve naturally – analogous to preemptive abandonment of the vulnerable roadway in the middle (three segments) of the domain in Figure 10 (from 1.5 - 3 km) decades before it is deemed untenable – a potential climate adaptation measure to avoid barrier drowning. A background erosion rate of 1 m/yr is included for all segments. Panel **a)** corresponds to the timing of roadway and community abandonment and panel **b)** is the final simulation state.

3.4.2 *Preemptive road removal scenario*

In our final scenario we implement partial, preemptive road removal as a potential climate adaptation measure for vulnerable roadways. We find that if the middle barrier segment is allowed to evolve naturally – that is, the road is preemptively abandoned long before management is deemed untenable – the neighboring community and roadway segments can both be managed for 137 years (Figure 11a), whereas in the status quo scenario, the middle roadway segments drowned at 71 years while they were still being managed (Figure 12b). When the road is preemptively removed, however, the community, is forced to nourish more frequently to 'hold the line' (every 2.9 years for the preemptive road removal scenario versus 3.4 years for the status quo scenario with accelerated SLR; Figure 12a) because the unmanaged (low, narrow) barrier segment is overwashed more frequently and therefore moves landward more rapidly.

The lack of management of the low, narrow, middle barrier segment in the preemptive road removal scenario also affects the fate of the barrier after management ceases (Figure 11b and Figure 12b). For each of the other accelerated SLR scenarios explored above, a portion of the barrier system drowns either while management is ongoing (Figure 7e, Figure 10c) or after management ceases (Figure 8e) due to dune-storm stochasticity: there is no storm of sufficient intensity to overtop the dunes and overwash the barrier (which would build it back up) before it is overcome by SLR. In contrast, in the preemptive road removal scenario, no barrier segments drown: a storm of sufficient intensity overwashes the entire barrier system after management ceases on either side of the natural (unmanaged) barrier segment, which allows the barrier system to keep pace with accelerated SLR. This may have occurred because of the timing of roadway and community abandonment (both 137 years), relative to the stochastic timing of an intense storm. However, a lack of management on the low, narrow (middle) barrier segment will tend to make drowning less likely system-wide by allowing more overwash on that segment, which induces more rapid shoreline retreat on adjacent segments, and thus more rapid retreat across the entire model domain after management ceases. More rapid shoreline retreat tends to erode dunes, making overwash more likely.

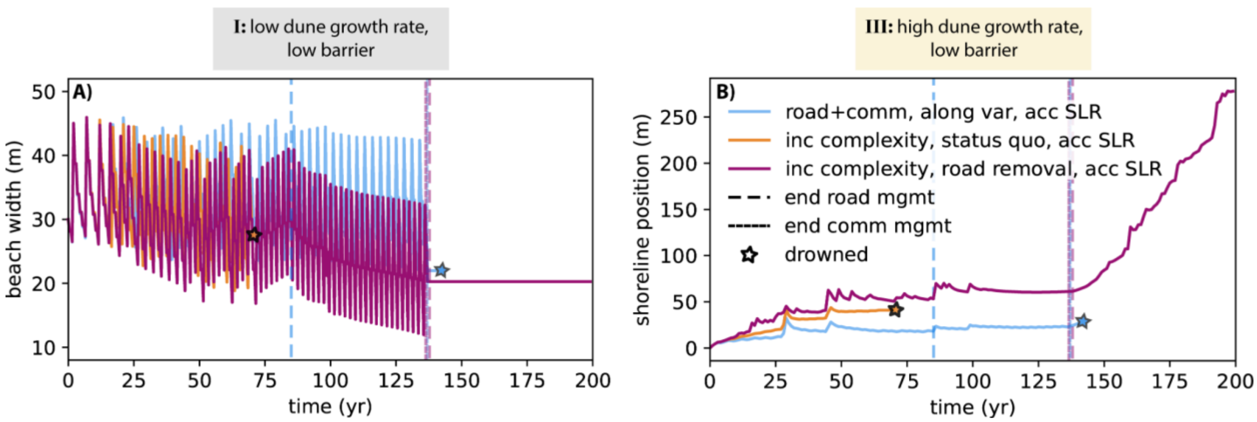

Figure 12. Time evolution of **a)** beach width (reported for a community segment) and **b)** shoreline position (reported for a roadway segment) for the increased alongshore complexity, status quo scenario (shown in Figure 10C) and preemptive road removal scenario (shown in Figure 11), both with accelerated SLR. Beach width time series corresponds to the middle barrier segment in the community at 0.5-1 km and the shoreline position time series corresponds to the barrier segment at 2-2.5 km, which is managed for a roadway in the status quo scenario and not managed in the preemptive road removal scenario. The increased alongshore complexity scenarios are compared to the roadway+community management, alongshore-variable initial configuration scenario with accelerated SLR (Figure 8c-e). The fine (coarse) dashed vertical lines delineate when community (roadway) management ceased for each simulation; stars indicate barrier drowning.

To examine these feedbacks in more detail, we evaluate the likelihood of barrier drowning for an additional 100 storm sequences for the increased alongshore complexity scenarios with accelerated SLR. The storm sequences were chosen randomly from the same suite of 10,000 synthetic storms (Reeves et al., 2021) with the same average number of storms per year (8). Table 2 shows that for 100 simulations, drowning occurs 81% of the time for the status quo scenario, with an average drowning time of 92 years. In contrast, drowning occurs 54% of the time for the preemptive road removal scenario, and the average drowning time is later (127 years). Hence, an outcome of this adaptation measure is that there is an increased likelihood of avoiding barrier drowning – a potentially undesirable system state (see Discussion) – and the roadway network, which here implicitly includes a bay-side bridge behind the unmanaged barrier segments, can be maintained as long as the barrier remains habitable for the adjacent community and roadway. Importantly, the average timescale of community habitability is unaffected by the preemptive road removal (137 years for both increased alongshore complexity scenarios, Table 2) and the timing of roadway abandonment on the 3-4.5 km barrier segments is on average only slightly decreased (133 years for the status quo scenario and 125 years for the preemptive road removal scenario). As before, the community is forced to nourish slightly more often on average due to overwashing of the unmanaged, middle barrier segment.

Table 2. Drowning and abandonment statistics for 100 storm sequences for the increased alongshore complexity scenarios with accelerated SLR (status quo, Figure 10C; preemptive road removal, Figure 11), and for the same scenarios with accelerated SLR but an increase in storminess (i.e., an increase in storm intensity and frequency). Percent refers to the number of simulations in which barrier drowning occurs. Abandonment statistics are calculated only for those simulations in which the community or roadway is abandoned, and in which drowning does not occur before management ceases in the specified segments.

	Barrier drowning (system-wide)				Community (0-1.5 km)				Roadway (1.5-3 km)			Roadway (3-4.5 km)		
Increased alongshore complexity scenarios (acc SLR)	%	time drowned (yr)			time abandoned (yr)			mean nourish. interval (yrs)	time abandoned (yr)			time abandoned (yr)		
		min	mean	max	min	mean	max		min	mean	max	min	mean	max
Status quo	81	71	92	150	132	137	138	3.06	46	57	82	110	133	161
Increased storminess	70	64	97	159	127	136	138	2.83	46	81	141	103	155	189
Preemptive road removal	54	85	127	152	132	137	138	2.58	--	--	--	109	125	161
Increased storminess	20	135	144	156	123	135	138	2.06	--	--	--	110	158	193

3.4.3 *Increased storminess*

There are other exogenous factors that could influence the timescale of barrier habitability, the probability and timing of barrier drowning, and therefore the long-term outcomes of adaptation measures in our model. We use a diffusive sediment transport model with a constant wave climate; if we were to change the wave climate in a way that increases or decreases the diffusivity of shoreline position – that is, how rapidly alongshore transport tends to smooth a coastline (e.g., Ashton and Murray, 2006) – this would alter shoreline retreat rates, which could feedback to alter dune-storm stochasticity and overwash flux. Climate-driven shifts in storm intensity (e.g., Knutson et al., 2020) could also influence dune-storm stochasticity through an increase in dune overtopping and overwash flux.

To investigate the impacts of an increase in 'storminess' – that is, an increase in annual overwash fluxes – we generate 100 new storm sequences and apply this forcing to the same increased alongshore complexity scenarios as before (status quo and preemptive road removal, both with accelerated SLR). Following the methodology of Reeves et al. (2021), we model an increase in storm intensity by shifting the distribution of R_{high} (the maximum runup) by +0.15 m such that storms with higher total water levels are preferentially selected from the suite of 10,000 synthetic storms. We then increase the average number of storms per year from 8 to 12. Statistics for the 100 simulations of increased storminess are shown in Table 2.

We find that for the status quo scenario, an increase in storminess results in a lower likelihood of barrier drowning (a decrease from 81% to 70%), but alongshore impacts on the timescales of management vary. For roadway segments, an increase in storminess results in more overwash flux, which increases the average timing of roadway abandonment (e.g., from 57 to 81 years for the middle roadway segment). The timescale of community habitability, however, is (on average) relatively unaffected by increases in storminess. Hence the principle exogenous factor governing the timing of community abandonment in our simulations is the rate of SLR. However, increased storminess does affect the community by driving increases in the frequency of nourishment.

The preemptive road removal scenario shows similar trends in response to increased storminess: a decrease in the occurrence of barrier drowning (from 54% to 20%), an increase in the average timescale of roadway abandonment (from 125 years to 158 years), and limited changes to community habitability.

For all increased alongshore complexity simulations, if nourishment can be maintained, enhanced storminess positively affects the habitability of barrier systems over long time scales by providing more overwash for recovery from vulnerable, low-lying states and a transition away from the (potentially undesirable) state of barrier drowning.

4 Discussion

With the newly developed landscape and human-dynamics modeling framework CASCADE, presented here, we provide new understandings of feedbacks between natural processes and human actions that modify coastal landscapes, as they unfold over time to alter the barrier state. These new understandings are facilitated by the capability of CASCADE to i) simulate the combined effects of management practices to protect roadways and community infrastructure, ii) resolve the role of dunes in overwash blockage more explicitly than previous models, iii) allow for alongshore variability in management strategies, and iv) apply a cellular flow routing model, which allows us to more thoroughly characterize modifications to the barrier interior arising from overwash delivery.

The long-time-scale dynamics that we explore here are largely an outgrowth of the details surrounding the blocking and filtering of overwash by different dune management strategies and infrastructure. This work advances the understanding provided by previous modeling efforts, namely that limiting overwash leads to the slow narrowing and lowering of barrier systems relative to rising sea level, and that human actions reduce the habitability of sandy coastlines by increasing vulnerability to acute (storm) and chronic (SLR) hazards (e.g., McNamara & Werner, 2008a, 2008b; Magliocca et al., 2011; Ells & Murray, 2012; Miselis & Lorenzo-Trueba, 2017; Rogers et al., 2015). We find that the possible sequences of states for a developed barrier system – that is, narrowing and lowering, followed by drowning or rebound – depend on internal system dynamics, initial conditions, exogenous conditions, and on the alongshore combinations of management strategies employed.

4.1 Dynamics of barrier segments managed for roadways or communities

As described previously, we define barriers as uninhabitable when the roadway or community drowns, or when a barrier becomes too narrow for the road to be relocated (roadway barrier management) or for a barrier to accommodate one row of homes and a roadway (community barrier management). Our model results demonstrate that for individual barrier segments (Figures 3-6), the pathway toward barrier uninhabitability is sensitive to both the initial configuration of the barrier interior, internal dune dynamics (growth rate and dune design height), and the randomness of storm occurrence and water level.

Under natural conditions, differences in dune growth rate (high versus low) result in different typical barrier morphologies, and a different range of autogenic variability (Figure S3). Barriers with dunes that have characteristically low growth rates will tend, overall, to be higher (i.e., have a higher average barrier interior elevation), and wider, than barriers with high dune growth rates. In addition, the range of multidecadal variability in interior island elevation and width is greater for barriers with high dune growth rates. This primarily stems from the tendency, under some conditions, for dunes to alternate between being tall and resistant to overwash, or low and vulnerable to overwash (Durán Vinent & Moore, 2015; Goldstein & Moore, 2016; Reeves et al., 2021; Vinent et al., 2021).

Because dune dynamics are tightly coupled to overwash flux, they have important implications for coastal management and the timescale of habitability. This is particularly true for dunes that are managed below the natural equilibrium dune crest elevation and therefore grow naturally, which primarily occurs in the 1-m and 2-m dune design-height roadway barrier-management scenarios. For example, the initial barrier configurations with a low dune growth rate, high barrier (configuration II) and high dune growth rate, high barrier (configuration IV) have similar starting topographies (Figure 2) but show marked differences in dune evolution (Figure 4) and subsequently, in overwash flux (Figure 3). This is because dunes recover slowly at a low dune growth rate, and are therefore frequently overtopped during storms (e.g., configuration II), leading to high overwash flux; conversely, dunes recover quickly at a high dune growth rate and are infrequently overtopped leading to low overwash flux (e.g., configuration IV). For the 1-m (2-m) dune design-height scenario, this results in an 18% (26%) higher cumulative overwash flux for barriers with low dune growth rates compared to barriers with high dune growth rates over the first 500 years of simulation. Because whether or not a dune is overtopped in its low state for either dune growth rate is a function of the randomness of storm occurrence and water level, the pathway toward uninhabitability and timing of abandonment is also governed in part by storm-dune stochasticity.

Whether or not a barrier drowns in our simulations after management ceases is also a function of dune-storm stochasticity. For the single storm sequence analyzed in the roadway barrier-management and community barrier-management scenarios (Figures 3-6), instances of barrier drowning occur in the absence of storms having sufficient intensity to overtop the tall remnant dune between the time when management ceases and SLR fully inundates the barrier interior (Figures 4, 6). Barrier segments with drowned barrier interiors may be more vulnerable to breaching, especially from the bayside (e.g., Sherwood et al., 2023). A potential adaptation measure to avoid drowning and return the barrier to a transgressive state could be to lower the dunes after management ceases to facilitate a higher probability of overwash. Other potential adaptation measures and levers for long-term resilience are discussed in more detail below (see Section 4.3).

Notably, most individual barrier segments managed for roadways or communities quickly rebound, showing increases in interior elevation and island width after management ceases, and approaching the autogenic variability of the natural equilibrium state by the end of the simulation (Figures 3, 5). It has been suggested that human alterations that increase the vulnerability of barrier systems may not be reversible over long time scales (e.g., Miselis & Lorenzo-Trueba, 2017). In contrast, our results demonstrate that following abandonment a negative (equilibrating) feedback can occur – driven by external dynamics in the form of sequential large storms – that facilitates a return to steady state. While this applies broadly to barrier elevation and width for all of the roadway barrier-management and community barrier-management scenarios (Figures 3-6), the cross-shore position remains lagged compared to what occurs in the natural scenarios at the end of the 1,000-year simulations, particularly for barrier segments managed for communities (Figure 5). This may be similar to the lag in shoreline retreat relative to changes in the rate of SLR identified by Mariotti and Hein (2022) – attributed to 'geomorphic capital', components of the barrier-shoreface system that are slow to adjust. In this case, prolonged beach nourishment adds sediment to the barrier and shoreface, compared to the natural scenarios, providing additional geomorphic capital which leads to reduced shoreline retreat. Due to limitations on projections for accelerations in SLR, we do not explore barrier rebound under accelerated SLR, which we hypothesize would not produce a steady state barrier elevation and width in our model over long (1,000-year) timescales.

4.2 Alongshore complexities

Developed barrier coastlines are rarely managed homogeneously over length scales of tens of kilometers. We find here that alongshore connectivity can lead to dynamical differences in barrier evolution for systems with alongshore variability in management strategies. By connecting adjacent barrier segments, our model results demonstrate that alongshore sediment transport results in alongshore feedbacks between dune-storm stochasticity and overwash flux, which subsequently influence timescales of habitability and potential changes in barrier state.

The impact of alongshore connectivity on shoreline behavior varies for each coastal management strategy we explored. For barrier systems that are only managed for roadways, the barrier is able to transgress landward in response to SLR and storms (black line in Figure 9b). When connected to adjacent communities that are nourishing, the shoreline positions of the roadway barrier segments are stabilized by the alongshore redistribution of sand. This 'suckers and freerider' effect (Williams et al., 2013) disappears after the community is abandoned and the roadway barrier segments return to a landward migrating state. (The cumulative effect of spreading the nourishment sediment from a community barrier segment to other barrier segments can be described as an alongshore distribution of geomorphic capital, with the consequence that the other barrier segments will also exhibit a lag in shoreline retreat, even after nourishment has ceased.) Conversely, if a roadway is abandoned first, curvature in the barrier system increases as the abandoned segments are overwashed and transgress landward. This results in larger alongshore sediment fluxes directed toward the overwashing segments, which requires adjacent communities to nourish more frequently (Figure 9c after 193 years). For the increased alongshore complexity, status quo scenarios (Figure 10), the addition of three roadway barrier segments to the model domain to create these scenarios both increases the number of overwashing segments and creates a longer length of coastline for sand from the community to be redistributed along (as compared to the roadway+community management, alongshore-variable initial configuration scenario in Figure 8). Generally, given the periodic boundary conditions of CASCADE, as the distance between stabilized shoreline segments in the model increases, shoreline erosion rates in between these stabilized segments increases, introducing more curvature in the barrier system and a need for more frequent nourishment in the community segments.

4.3 Outcomes of adaptation measures and levers to support long-term resilience

The modeling framework presented here can be used to evaluate the potential effectiveness of adaptation strategies over multidecadal timescales for different combinations of endogenous and exogenous conditions, and the long-term feedbacks associated with management actions. For the climate adaptation measure explored here – preemptive abandonment of a roadway segment decades before it is deemed untenable (Figures 11-12), motivated by a 3-km bridge built landward of the barrier north of Rodanthe, NC, USA in 2022 – we found that the sequence of states for the barrier system was altered due to complex human-natural feedbacks that unfold over many decades. Specifically, by allowing part of the barrier to preemptively return to its natural overwashing state, drowning was less likely to occur system-wide (Table 2). This occurs because more overwash at the location of the former roadway induces more rapid shoreline retreat along that barrier segment. This, in turn, causes more rapid shoreline retreat, dune erosion, and overwash along adjacent segments after roadway and community management cease at 137 years (Figure 11a) as these features quickly 'catch up' with the landward transgression of the middle barrier segment. This feedback is exacerbated by an increase in storminess – here defined as an increase in annual overwash flux due to climate-driven increases in storm intensity and frequency – which further decreases the likelihood of barrier drowning. The increase in overwash flux due to enhanced storminess prolongs the timescale of roadway management but has negligible impacts on the timing of community uninhabitability, which is principally governed by the rate of SLR. Hence, communities are affected by increased storminess primarily through an increase in nourishment frequency. Overall, we find that enhanced storminess can, under some circumstances, positively affect the habitability of barrier systems by providing more overwash for recovery from vulnerable, low-lying states and a transition away from the potentially undesirable state of barrier drowning, assuming 1) some amount of overwash can reach the island interior and remain there and 2) that nourishment in communities can be maintained.

As communities, governments, and civil society groups explore levers for long-term resilience – which may include adaptation measures that involve partially abandoning or modifying dune and beach management strategies along particularly vulnerable barrier segments – our findings suggest that there needs to be consideration of the effects of interactions between dune dynamics and storm overwash potential, alongshore connectivity of management strategies, and long-time-scale dynamics when assessing which management practices are likely to enhance resilience as intended. Given the importance of dune-storm stochasticity to the occurrence and timing of barrier drowning, the range of potential outcomes for adaptation measures will require simulating many storm sequences for different projections of SLR and storminess.

Additional considerations not explored here, but which are important at the community scale for determining the effectiveness of different adaptation measures as levers for long-term resilience, include geomorphic-economic feedbacks. Coastal real-estate markets are dynamically linked to characteristics of the coastal landscape (e.g., beach width and dune height) and therefore both drive and respond to beach and dune management practices (e.g., Brown & Pollakowski, 1977; Gopalakrishnan et al., 2011; McNamara et al., 2011; McNamara & Keeler, 2013). As coastal real-estate markets change and ultimately begin to unravel in the future, the economic feasibility and utility of different levers will also shift.

4.4 Model limitations

As an 'appropriate-complexity' model (French et al., 2016), CASCADE by design only resolves what are believed to be the most essential processes for exploring potential state changes in developed barrier systems. However, there are other endogenous processes that may be important and could be fruitful to explore in future work. Dune erosion and recovery can be influenced by beach dynamics, which are not included in our model. For example, wave runup is lower on wider, more gently sloping beaches (Ruggiero et al., 2004; Stockdon et al., 2006), and consequently, dunes fronted by wide beaches experience less erosion (from dune collision) than those found on narrow beaches (Beuzen et al., 2019; Itzkin et al., 2021). Therefore, incorporating the effects of beach width on dune erosion and recovery could influence dune-storm stochasticity.

We also assume that engineered dunes grow naturally to an equilibrium crest elevation, which in some locations may not be true; for example, where dunes have limited vegetation and are rebuilt so often that they are just piles of unvegetated sand (as is the case north of Rodanthe, NC, USA; Sciaudone et al., 2016). Scarping and slumping of the dune face tends to contribute to dune height loss but is also not explicitly modeled in Barrier3D. The inclusion of these processes would tend to reduce the ability of dunes to remain in a tall state and thereby allow for more frequent overwash deposition in the barrier interior; without these processes, drowning of the barrier interior when dunes are tall is likely overestimated in our model. Conversely, the storm sequences used in our simulations do not include storms with water levels high enough to cause inundation (Sallenger, 2000), which can remove sediment from barriers, and therefore could increase the likelihood of drowning.

Lastly, while not explicitly modeled, drowned barrier segments could become breaches or inlets given sufficient flows, or lead to island disintegration (Moore et al., 2014; Passeri et al., 2020). Alternatively, these segments could be infilled quickly through alongshore sediment transport processes. Future work should incorporate the effects of breaching and inlet processes.

5 Conclusions

We address the long-term future of developed barrier systems, modeling both the human and natural factors that influence the evolution of barrier states over decades to centuries. Simulations developed using the new CASCADE modeling framework demonstrate that future barrier state and habitability depend on both human and natural factors, including internal system dynamics (dune growth and recovery rates), initial barrier configuration (barrier width and elevation), exogenous conditions (storm sequence, storminess, and SLR), and the alongshore combinations of management strategies (here, beach and dune management to maintain communities and roadways).

After roadway and community management have been abandoned, which can occur as soon as 46 years into a simulation or take as long as 500+ years, barrier segments attain one of two new states: either they experience drowning (defined in this context as submergence of the barrier interior, landward of the dune) or they recover to a less vulnerable state through restoration of barrier elevation and width via storm overwash. The occurrence of barrier drowning depends on dune-storm stochasticity – that is, the randomness of a storm occurring with sufficient intensity to overtop remaining tall dunes, and thereby increase island height and width, between the time when management ceases and SLR fully inundates the barrier interior. For barriers that do not drown, under linear SLR, we find that in some cases, human alterations to barrier systems are reversible over decadal to centurial time scales, with some barriers rebounding to steady state geometries in just a few decades.

We find that preemptive abandonment of a vulnerable roadway decreases the probability of barrier drowning but requires increased nourishment rates in adjacent communities to 'hold the line'. Simulations that incorporate potential increases in storm intensity and frequency (i.e., increased storminess) suggest a barrier system is less vulnerable to drowning under these conditions due to an increase in overwash along the most vulnerable, low-lying barrier segments, as long as overwash is allowed to reach the island interior. There are also alongshore feedbacks: more overwash along abandoned barrier segments enhances curvature in the barrier system, and larger alongshore sediment fluxes are directed toward overwashing segments. More overwash along abandoned portions of a barrier system also enhances the natural rebound of adjacent barrier segments after management ceases on these segments.

As communities explore potential levers that may allow unfavorable outcomes or system states to be avoided, our findings point to the critical importance of considering coupled human-natural interactions and the role of storm stochasticity when evaluating the likely effect of short-term decisions on the long-term (decadal to centurial) resilience of coastal communities and landscapes.

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Open Research

Upon publication, CASCADE will be available for download from the online CSDMS model repository at https://csdms.colorado.edu/wiki/Model:CASCADE and is currently available on GitHub at https://github.com/UNC-CECL/CASCADE. Data for model experiments are in the repository at DOI: 10.6084/m9.figshare.22295413.

References

Armstrong, S. B., & Lazarus, E. D. (2019). Masked Shoreline Erosion at Large Spatial Scales as a Collective Effect of Beach Nourishment. *Earth's Future*, *7*(2), 74–84. https://doi.org/10.1029/2018EF001070

Armstrong, S. B., Lazarus, E. D., Limber, P. W., Goldstein, E. B., Thorpe, C., & Ballinger, R. C. (2016). Indications of a positive feedback between coastal development and beach nourishment. *Earth's Future*, *4*(12), 626–635. https://doi.org/10.1002/2016EF000425

Ashton, A. D., & Lorenzo-Trueba, J. (2018). Morphodynamics of Barrier Response to Sea-Level Rise. In L. J. Moore & A. B. Murray (Eds.), *Barrier Dynamics and Response to Changing Climate* (pp. 277–304). Springer International Publishing. https://doi.org/10.1007/978-3-319-68086-6_9

Ashton, A. D., & Murray, A. B. (2006). High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. *Journal of Geophysical Research: Earth Surface*, *111*(F4). https://doi.org/10.1029/2005JF000422

Beuzen, T., Harley, M. D., Splinter, K. D., & Turner, I. L. (n.d.). Controls of variability in berm and dune storm erosion. *Journal of Geophysical Research: Earth Surface*, *n/a*(n/a). https://doi.org/10.1029/2019JF005184

Brown, G. M., & Pollakowski, H. O. (1977). Economic Valuation of Shoreline. *The Review of Economics and Statistics*, *59*(3), 272–278. https://doi.org/10.2307/1925045

Cooper, J. A. G., & McKenna, J. (2009). Boom and Bust: The Influence of Macroscale Economics on the World's Coasts. *Journal of Coastal Research*, *25*(3 (253)), 533–538. https://doi.org/10.2112/09A-0001.1

Dolan, R. (2020). Barrier islands: natural and controlled. In *Coastal Geomorphology* (pp. 263-278). Routledge.

Douglass, S. L., Webb, B. M., & United States. Federal Highway Administration. Office of Bridges and Structures. (2020). *Highways in the Coastal Environment: Hydraulic Engineering Circular Number 25 - Third Edition* (FHWA-HIF-19-059). https://rosap.ntl.bts.gov/view/dot/55727

Durán, O., & Moore, L. J. (2013). Vegetation controls on the maximum size of coastal dunes. *Proceedings of the National Academy of Sciences, 110(43)*, 17217-17222. https:/doi.org/10.1073/pnas.1307580110

Durán Vinent, O., & Moore, L. J. (2015). Barrier island bistability induced by biophysical interactions. *Nature Climate Change*, *5*(2), 158–162. https://doi.org/10.1038/nclimate2474

Elko, N., Briggs, T. R., Benedet, L., Robertson, Q., Thomson, G., Webb, B. M., & Garvey, K. (2021). A century of U.S. beach nourishment. *Ocean & Coastal Management, 199*, 105406. https://doi.org/10.1016/j.ocecoaman.2020.105406

Ells, K., & Murray, A. B. (2012). Long-term, non-local coastline responses to local shoreline stabilization. *Geophysical Research Letters*, *39*(19). https://doi.org/10.1029/2012GL052627

Ferguson, R. I., & Church, M. (2004). A Simple Universal Equation for Grain Settling Velocity. *Journal of Sedimentary Research*, *74*(6), 933–937. https://doi.org/10.1306/051204740933

French, J., Payo, A., Murray, B., Orford, J., Eliot, M., & Cowell, P. (2016). Appropriate complexity for the prediction of coastal and estuarine geomorphic behaviour at decadal to centennial scales. *Geomorphology, 256*, 3-16. https://doi.org/10.1016/j.geomorph.2015.10.005

Gilbert, G. K. (1885). *The Topographic Features of Lake Shores*. U.S. Government Printing Office.

Goldstein, E. B., & Moore, L. J. (2016). Stability and bistability in a one-dimensional model of coastal foredune height. *Journal of Geophysical Research: Earth Surface*, *121*(5), 964–977. https://doi.org/10.1002/2015JF003783

Gopalakrishnan, S., McNamara, D., Smith, M. D., & Murray, A. B. (2017). Decentralized Management Hinders Coastal Climate Adaptation: The Spatial-dynamics of Beach Nourishment. *Environmental and Resource Economics*, *67*(4), 761–787. https://doi.org/10.1007/s10640-016-0004-8

Gopalakrishnan, S., Smith, M. D., Slott, J. M., & Murray, A. B. (2011). The value of disappearing beaches: A hedonic pricing model with endogenous beach width. *Journal of Environmental Economics and Management*, *61*(3), 297–310. https://doi.org/10.1016/j.jeem.2010.09.003

Hallermeier, R. J. (1980). A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering*, *4*, 253–277. https://doi.org/10.1016/0378-3839(80)90022-8

Houser, C. (2013). Alongshore variation in the morphology of coastal dunes: Implications for storm response. *Geomorphology*, *199*, 48–61. https://doi.org/10.1016/j.geomorph.2012.10.035

Intergovernmental Panel on Climate Change. (2014). *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Itzkin, M., Moore, L. J., Ruggiero, P., & Hacker, S. D. (2020). The effect of sand fencing on the morphology of natural dune systems. *Geomorphology*, *352*, 106995. https://doi.org/10.1016/j.geomorph.2019.106995

Itzkin, M., Moore, L. J., Ruggiero, P., Hacker, S. D., & Biel, R. G. (2021). The relative influence of dune aspect ratio and beach width on dune erosion as a function of storm duration and surge level. *Earth Surface Dynamics*, *9*(5), 1223–1237. https://doi.org/10.5194/esurf-9-1223-2021

Jin, D., Hoagland, P., & Ashton, A. D. (2022). Risk averse choices of managed beach widths under environmental uncertainty. *Natural Resource Modeling*, 35(1), e12324. https://doi.org/10.1111/nrm.12324

Karanci, A., Velásquez-Montoya, L., Paniagua-Arroyave, J. F., Adams, P. N., & Overton, M. F. (2018). Beach management practices and occupation dynamics: an agent-based modeling study for the coastal town of Nags Head, NC, USA. In Beach Management Tools-Concepts, Methodologies and Case Studies (pp. 373-395). Springer, Cham.

Keeler, A. G., McNamara, D. E., & Irish, J. L. (2018). Responding to Sea Level Rise: Does Short-Term Risk Reduction Inhibit Successful Long-Term Adaptation? *Earth's Future*, *6*(4), 618–621. https://doi.org/10.1002/2018EF000828

Landry, C. E., & Hindsley, P. (2011). Valuing beach quality with hedonic property models. *Land Economics*, 87(1), 92-108. https://doi.org/10.3368/le.87.1.92

Lazarus, E. D., Ellis, M. A., Brad Murray, A., & Hall, D. M. (2016). An evolving research agenda for human–coastal systems. *Geomorphology*, *256*, 81–90. https://doi.org/10.1016/j.geomorph.2015.07.043

Lazarus, E. D., Goldstein, E. B., Taylor, L. A., & Williams, H. E. (2021). Comparing Patterns of Hurricane Washover into Built and Unbuilt Environments. *Earth's Future*, *9*(3), e2020EF001818. https://doi.org/10.1029/2020EF001818

Leatherman, S. P. (1979). Migration of Assateague Island, Maryland, by inlet and overwash processes. *Geology*, *7*(2), 104–107. https://doi.org/10.1130/0091-7613(1979)7<104:MOAIMB>2.0.CO;2

Leatherman, S. P. (1983). Barrier dynamics and landward migration with Holocene sea-level rise. *Nature*, *301*(5899), 415–417. https://doi.org/10.1038/301415a0

Lorenzo-Trueba, J., & Ashton, A. D. (2014). Rollover, drowning, and discontinuous retreat: Distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model. *Journal of Geophysical Research: Earth Surface*, *119*(4), 779–801. https://doi.org/10.1002/2013JF002941

Lorenzo-Trueba, J., & Mariotti, G. (2017). Chasing boundaries and cascade effects in a coupled barrier-marsh-lagoon system. *Geomorphology*, *290*, 153–163. https://doi.org/10.1016/j.geomorph.2017.04.019

Magliocca, N. R., McNamara, D. E., & Murray, A. B. (2011). Long-Term, Large-Scale Morphodynamic Effects of Artificial Dune Construction along a Barrier Island Coastline. *Journal of Coastal Research*, 918–930. https://doi.org/10.2112/JCOASTRES-D-10-00088.1

Mariotti, G. (2021). Self-Organization of Coastal Barrier Systems During the Holocene. *Journal of Geophysical Research: Earth Surface, 126(5)*, e2020JF005867. https://doi.org/10.1029/2020JF005867

Mariotti, G., & Hein, C. J. (2022). Lag in response of coastal barrier-island retreat to sea-level rise. *Nature Geoscience*, *15*(8), 633–638. https://doi.org/10.1038/s41561-022-00980-9

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, Ö., Yu, R., & Zhou, B. (Eds.). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Mellett, C. L., Hodgson, D. M., Lang, A., Mauz, B., Selby, I., & Plater, A. J. (2012). Preservation of a drowned gravel barrier complex: A landscape evolution study from the north-eastern English Channel. *Marine Geology*, 315, 115-131. https://doi.org/10.1016/j.margeo.2012.04.008

Mellett, C. L., & Plater, A. J. (2018). Drowned barriers as archives of coastal-response to sea-level rise. *Barrier dynamics and response to changing climate*, 57-89.

Mull, J., & Ruggiero, P. (2014). Estimating storm-induced dune erosion and overtopping along US West Coast beaches. *Journal of Coastal Research, 30*(6), 1173-1187. https://doi.org/10.2112/JCOASTRES-D-13-00178.1

McNamara, D. E., Gopalakrishnan, S., Smith, M. D., & Murray, A. B. (2015). Climate Adaptation and Policy-Induced Inflation of Coastal Property Value. *PLOS ONE*, *10*(3), e0121278. https://doi.org/10.1371/journal.pone.0121278

McNamara, D. E., & Keeler, A. (2013). A coupled physical and economic model of the response of coastal real estate to climate risk. *Nature Climate Change*, *3*(6), 559–562. https://doi.org/10.1038/nclimate1826

McNamara, D. E., Murray, A. B., & Smith, M. D. (2011). Coastal sustainability depends on how economic and coastline responses to climate change affect each other. *Geophysical Research Letters, 38*(7). https://doi.org/10.1029/2011GL047207

McNamara, D. E., & Werner, B. T. (2008a). Coupled barrier island–resort model: 1. Emergent instabilities induced by strong human-landscape interactions. *Journal of Geophysical Research: Earth Surface*, *113*(F1). https://doi.org/10.1029/2007JF000840

McNamara, D. E., & Werner, B. T. (2008b). Coupled barrier island–resort model: 2. Tests and predictions along Ocean City and Assateague Island National Seashore, Maryland. *Journal of Geophysical Research: Earth Surface*, *113*(F1). https://doi.org/10.1029/2007JF000841

Mellett, C. L., & Plater, A. J. (2018). Drowned Barriers as Archives of Coastal-Response to Sea-Level Rise. In L. J. Moore & A. B. Murray (Eds.), *Barrier Dynamics and Response to Changing Climate* (pp. 57–89). Springer International Publishing. https://doi.org/10.1007/978-3-319-68086-6_2

Mileti, D. (1999). *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Joseph Henry Press.

Miselis, J. L., & Lorenzo-Trueba, J. (2017). Natural and Human-Induced Variability in Barrier-Island Response to Sea Level Rise. *Geophysical Research Letters*, *44*(23), 11,922-11,931. https://doi.org/10.1002/2017GL074811

Moore, L. J., List, J. H., Williams, S. J., & Stolper, D. (2010). Complexities in barrier island response to sea level rise: Insights from numerical model experiments, North Carolina Outer Banks. *Journal of Geophysical Research: Earth Surface*, *115*(F3). https://doi.org/10.1029/2009JF001299

Moore, L. J., & Murray, A. B. (Eds.). (2018). *Barrier Dynamics and Response to Changing Climate*. Springer International Publishing. https://doi.org/10.1007/978-3-319-68086-6

Moore, L. J., Patsch, K., List, J. H., & Williams, S. J. (2014). The potential for sea-level-rise-induced barrier island loss: Insights from the Chandeleur Islands, Louisiana, USA. *Marine Geology*, *355*, 244–259. https://doi.org/10.1016/j.margeo.2014.05.022

Murray, A. B. (2003). Contrasting the Goals, Strategies, and Predictions Associated with Simplified Numerical Models and Detailed Simulations. In *Prediction in Geomorphology* (pp. 151–165). American Geophysical Union (AGU). https://doi.org/10.1029/135GM11

Murray, A. B. (2013). 2.5 Which Models Are Good (Enough), and When? In J. F. Shroder (Ed.), *Treatise on Geomorphology* (pp. 50–58). Academic Press. https://doi.org/10.1016/B978-0-12-374739-6.00027-0

Murray, A. B., & Paola, C. (1994). A cellular model of braided rivers. *Nature*, *371*(6492), 54–57. https://doi.org/10.1038/371054a0

Murray, A. B., & Paola, C. (1997). Properties of a cellular braided-stream model. *Earth Surface Processes and Landforms*, *22*(11), 1001–1025. https://doi.org/10.1002/(SICI)1096-9837(199711)22:11<1001::AID-ESP798>3.0.CO;2-O

Article 8. - DISTRICT DEVELOPMENT STANDARDS, 8 Code of Ordinances (2022). https://library.municode.com/nc/nags_head/codes/code_of_ordinances?nodeId=PTIIUNDEOR_ART8DIDEST_S8.4DESTSPDI

NCDOT. (2022, August 5). *N.C. 12 Rodanthe Bridge*. https://www.ncdot.gov/projects/nc-12-rodanthe/Pages/NCDOT

Nienhuis, J. H. (2019). Effect of tidal inlet stabilization on barrier island morphodynamics. In *Coastal Sediments 2019* (pp. 85–90). WORLD SCIENTIFIC. https://doi.org/10.1142/9789811204487_0008

Nienhuis, J. H., & Lorenzo-Trueba, J. (2019a). Simulating barrier island response to sea level rise with the barrier island and inlet environment (BRIE) model v1.0. *Geoscientific Model Development*, *12*(9), 4013–4030. https://doi.org/10.5194/gmd-12-4013-2019

Nienhuis, J. H., & Lorenzo-Trueba, J. (2019b). Can Barrier Islands Survive Sea-Level Rise? Quantifying the Relative Role of Tidal Inlets and Overwash Deposition. *Geophysical Research Letters*, *46*(24), 14613–14621. https://doi.org/10.1029/2019GL085524

Nordstrom, K. F. (1994). Beaches and dunes of human-altered coasts. *Progress in Physical Geography: Earth and Environment*, *18*(4), 497–516. https://doi.org/10.1177/030913339401800402

Nordstrom, K. F. (2004). *Beaches and Dunes of Developed Coasts*. Cambridge University Press.

Nordstrom, K. F., & Jackson, N. L. (1995). Temporal scales of landscape change following storms on a human-altered coast, New Jersey, USA. *Journal of Coastal Conservation*, *1*(1), 51–62. https://doi.org/10.1007/BF02835562

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157964

Ortiz, A. C., & Ashton, A. D. (2016). Exploring shoreface dynamics and a mechanistic explanation for a morphodynamic depth of closure. *Journal of Geophysical Research: Earth Surface*, *121*(2), 442–464. https://doi.org/10.1002/2015JF003699

Passeri, D. L., Dalyander, P. S., Long, J. W., Mickey, R. C., Jenkins, R. L., Thompson, D. M., Plant, N. G., Godsey, E. S., & Gonzalez, V. M. (2020). The Roles of Storminess and Sea Level Rise in Decadal Barrier Island Evolution. *Geophysical Research Letters*, *47*(18). https://doi.org/10.1029/2020GL089370

Rampino, M. R., & Sanders, J. E. (1980). Holocene transgression in south-central Long Island, New York. *Journal of Sedimentary Research*, 50(4), 1063-1079. https://doi.org/10.1306/212F7B7B-2B24-11D7-8648000102C1865D

Reeves, I. R. B., Moore, L. J., Murray, A. B., Anarde, K. A., & Goldstein, E. B. (2021). Dune Dynamics Drive Discontinuous Barrier Retreat. *Geophysical Research Letters*, *48*(13), e2021GL092958. https://doi.org/10.1029/2021GL092958

Reeves, I., Anarde, K., & Moore, L. J. (2021). Record of storm events and associated water levels for the Virginia Coast Reserve, 1980-2013. Virginia Coast Reserve Long-Term Ecological Research Project Data Publication knb-lter-vcr.352.1 (https://www.vcrlter.virginia.educgi-bin/showDataset.cgi?docid=knb-lter-vcr.352.1).

Rogers, L. J., Moore, L. J., Goldstein, E. B., Hein, C. J., Lorenzo-Trueba, J., & Ashton, A. D. (2015). Anthropogenic controls on overwash deposition: Evidence and consequences. *Journal of Geophysical Research: Earth Surface*, *120*(12), 2609–2624. https://doi.org/10.1002/2015JF003634

Rohling, E. J., Haigh, I. D., Foster, G. L., Roberts, A. P., & Grant, K. M. (2013). A geological perspective on potential future sea-level rise. *Scientific Reports*, *3*(1), 3461. https://doi.org/10.1038/srep03461

Ruggiero, P., Holman, R. A., & Beach, R. A. (2004). Wave run-up on a high-energy dissipative beach. *Journal of Geophysical Research: Oceans*, *109*(C6). https://doi.org/10.1029/2003JC002160

Sallenger Jr, A. H. (2000). Storm impact scale for barrier islands. *Journal of Coastal Research*, 890-895.

Sherwood, C. R., Ritchie, A. C., Over, J. S. R., Kranenburg, C. J., Warrick, J. A., Brown, J. A., ... & Hegermiller, C. A. (2023). Sound-Side Inundation and Seaward Erosion of a Barrier Island During Hurricane Landfall. *Journal of Geophysical Research: Earth Surface*, *128*(1), e2022JF006934.

Sciaudone, E. J., Velasquez-Montoya, L., Smyre, E. A., & Overton, M. F. (2016). *Pea Island, North Carolina*. *84*(2), 10.

Slott, J. M., Murray, A. B., Ashton, A. D., & Crowley, T. J. (2006). Coastline responses to changing storm patterns. *Geophysical Research Letters*, *33*(18). https://doi.org/10.1029/2006GL027445

Slott, J. M., Smith, M. D., & Murray, A. B. (2008). Synergies between adjacent beach-nourishing communities in a morpho-economic coupled coastline model. *Coastal Management, 36*(4), 374-391. https://doi.org/10.1080/08920750802266429

Slott, J. M., Murray, A. B., & Ashton, A. D. (2010). Large-scale responses of complex-shaped coastlines to local shoreline stabilization and climate change. *Journal of Geophysical Research: Earth Surface*, *115*(F3). https://doi.org/10.1029/2009JF001486

Stockdon, H. F., Holman, R. A., Howd, P. A., & Sallenger, A. H. (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, *53*(7), 573–588. https://doi.org/10.1016/j.coastaleng.2005.12.005

Stolper, D., List, J. H., & Thieler, E. R. (2005). Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behaviour model (GEOMBEST). *Marine Geology*, *218*(1), 17–36. https://doi.org/10.1016/j.margeo.2005.02.019

Storms, J. E. A. (2003). Event-based stratigraphic simulation of wave-dominated shallow-marine environments. *Marine Geology*, *199*(1), 83–100. https://doi.org/10.1016/S0025-3227(03)00144-0

Storms, J. E. A., Weltje, G. J., van Dijke, J. J., Geel, C. R., & Kroonenberg, S. B. (2002). Process-Response Modeling of Wave-Dominated Coastal Systems: Simulating Evolution and Stratigraphy on Geological Timescales. *Journal of Sedimentary Research*, *72*(2), 226–239. https://doi.org/10.1306/052501720226

Straub, J. A., Rodriguez, A. B., Luettich, R. A., Moore, L. J., Itzkin, M., Ridge, J. T., Seymour, A. C., Johnston, D. W., & Theuerkauf, E. J. (2020). The role of beach state and the timing of pre-storm surveys in determining the accuracy of storm impact assessments. *Marine Geology, 425*, 106201. https://doi.org/10.1016/j.margeo.2020.106201

Tenebruso, C., Nichols-O'Neill, S., Lorenzo-Trueba, J., Ciarletta, D. J., & Miselis, J. L. (2022). Undeveloped and developed phases in the centennial evolution of a barrier-marsh-lagoon system: The case of Long Beach Island, New Jersey. *Frontiers in Marine Science*, 9. https://doi.org/10.3389/fmars.2022.958573

Turner, R. K. (2000). Integrating natural and socio-economic science in coastal management. *Journal of Marine Systems*, *25*(3), 447–460. https://doi.org/10.1016/S0924-7963(00)00033-6

Velasquez-Montoya, L., Sciaudone, E. J., Smyre, E., & Overton, M. F. (2021). Vulnerability Indicators for Coastal Roadways Based on Barrier Island Morphology and Shoreline Change Predictions. *Natural Hazards Review*, *22*(2), 04021003. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000441

Vinent, O. D., Schaffer, B. E., & Rodriguez-Iturbe, I. (2021). Stochastic dynamics of barrier island elevation. *Proceedings of the National Academy of Sciences*, *118*(1), e2013349118. https://doi.org/10.1073/pnas.2013349118

Werner, B. T., & McNamara, D. E. (2007). Dynamics of coupled human-landscape systems. *Geomorphology*, *91*(3), 393–407. https://doi.org/10.1016/j.geomorph.2007.04.020

Williams, Z. C., McNamara, D. E., Smith, M. D., Murray, A. Brad., & Gopalakrishnan, S. (2013). Coupled economic-coastline modeling with suckers and free riders. *Journal of Geophysical Research: Earth Surface*, *118*(2), 887–899. https://doi.org/10.1002/jgrf.20066