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

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Key Points:

- Counterintuitively, with higher dune design heights and lower/wider initial barrier geometries, barriers become uninhabitable sooner
- Randomness in dune-storm interactions dictates whether or not a barrier drowns after management ceases
- Simulations suggest barrier systems can recover in height, width, and cross-shore position quickly (within decades) after management ceases

Abstract

Many barrier islands and spits (collectively, "barriers") throughout the world are highly developed. As low-lying, sandy coastal landforms, barrier systems are naturally reshaped by processes associated with storms and sea-level rise (SLR). The resulting landscape changes threaten development, and in response, humans employ defensive measures that physically modify barrier geometry to reduce relatively short-term risk. These measures include the construction of large dunes, emplacement of beach nourishment, and removal of overwash deposition. Simulations conducted using a new coupled modeling framework show that, over decades to centuries, measures to protect roadways and communities alter the physical characteristics of barrier systems in ways that ultimately limit their habitability. 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 – because building dunes blocks overwash delivery to the barrier interior – and on initial conditions (barrier elevation and width). In the model, barriers can become lower and narrower with SLR to the point of drowning. The timing and occurrence of barrier drowning depends on randomness in the timing and intensity of storms and dune recovery processes. We find that under a constant rate of SLR, negative feedbacks involving storms can allow barriers that do not drown to rebound toward steady-state geometries within decades after management practices cease.

Plain Language Summary

Barrier islands and spits (collectively referred to as "barriers") can naturally keep up with sea-level rise primarily through a process called overwash. During overwash, sand from the beach is washed landward past the dunes by storm waves, leading to increases in barrier height (elevation) and width. Tall dunes, built to protect roadways and oceanfront 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, which then block future overwash deposition, is the narrowing and lowering of barriers relative to sea level. 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.

1 Introduction

Along sandy coastlines, chronic shoreline erosion resulting from alongshore movement of sediment can be superimposed on long-term erosion induced by sea-level rise (SLR), which is especially important for low-lying barrier islands and spits (hereafter referred to collectively as "barriers"; Moore & Murray, 2018; Leatherman, 1979, 1983). During intense storms, waves remove sand from the nearshore seabed, beach and dunes, and deposit it on top of barriers as washover. 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., Landry & Hindsley, 2011; Jin et al., 2022; Nordstrom, 1994, 2004), and removal of overwash deposited on roads (Lazarus & Goldstein, 2019; 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., Magliocca et al., 2011; McNamara & Werner, 2008a,b). Over long time scales (decades to centuries), if barriers do not migrate upward and landward, they can drown (Gilbert, 1885; Lorenzo-Trueba & Ashton, 2014; Mellett & Plater, 2018; Moore et al., 2010; Storms et al., 2002). In contrast, when overwashed sand remains, barriers become less vulnerable to SLR and future storms (Dolan, 1980; Miselis & Lorenzo-Trueba, 2017; Rogers et al., 2015).

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

Modeling of decade to century-scale evolution of human-occupied barriers is limited (Karanci et al., 2018; Magliocca et al., 2011; McNamara & Werner, 2008a,b; Miselis & Lorenzo-Trueba, 2017; Rogers et al., 2015; Tenebruso et al., 2022), in part because it is challenging, involving human and natural dynamics that interact across nested spatial scales (Hoagland et al., 2023), 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,b); 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).

Investigation of 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). In the work presented here, we use this new, coupled model to explore how management actions (i.e., dune construction, road relocation, beach nourishment, and overwash removal) – undertaken to protect barrier communities and roads from storms, and the chronic effects of SLR – 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 (Murray 2003), 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. In a companion paper, Anarde et al. (2024a), we further explore these dynamics and the complexities that emerge when considering accelerations in SLR and changes in storm intensity and frequency, as well as alongshore variability in management strategies.

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. Optionally, CASCADE can also simulate large-scale coastline evolution arising from alongshore sediment transport processes (see Anarde et al., 2024a). 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 (Lorenzo-Trueba & Ashton, 2014; Lorenzo-Trueba &

Mariotti, 2017; Moore et al., 2010; Storms, 2003; Stolper et al., 2005) 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.

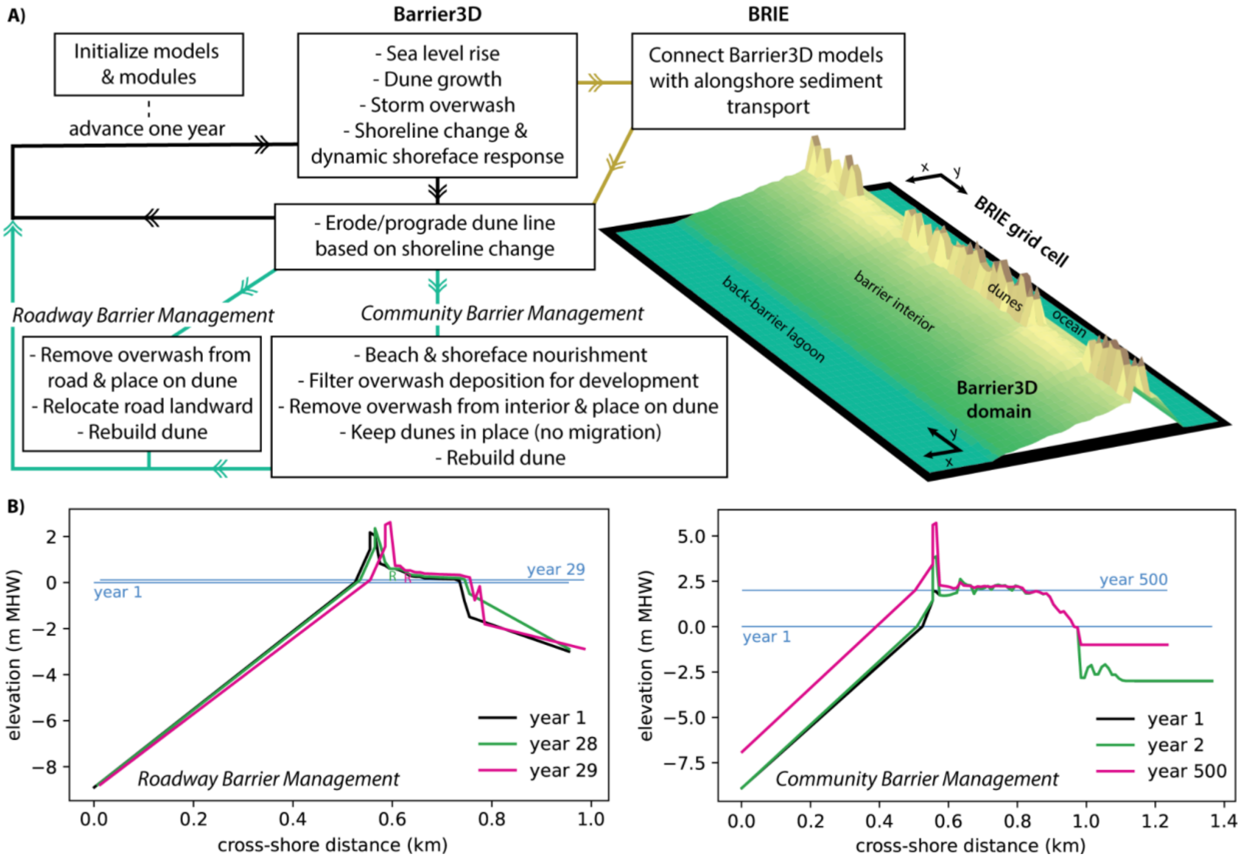

Figure 1. a) CASCADE time loop and coupled model domain. Two human-dynamics modules (italicized) modify the Barrier3D model domain. Green and yellow arrows indicate optional coupling pathways. b) Example cross sections illustrating the human dynamics simulated in each module. In the roadway-barrier management module, the road is relocated after the dune migrates onto the roadway due to barrier transgression (left panel: 'R' corresponds to the roadway location in each model year; road relocation occurs in year 29). In this module, dunes are rebuilt to a height relative to the roadway elevation (here, 2-m above the road). In the community-barrier management module, the barrier is maintained at a fixed cross-shore position through nourishment, which involves placement of a volume of sand along the entire shoreface when the beach falls below a minimum width (here, 30 m; shown in the right panel between year 1 and 2). In this module, dunes are rebuilt to the same elevation relative to the time-invariant berm crest, which keeps pace with SLR.

A barrier segment in Barrier3D is composed of 10 x 10 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 1a), 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; Mellet and Plater, 2018; Rampino & Sanders, 1980) 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 (i.e., Ashton & Murray, 2006) housed within the BRIE model, which distributes sediment alongshore amongst the different connected barrier segments (with periodic boundary conditions at the outermost boundaries). 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 1a), and 3) turning off all other model processes within BRIE (i.e., the 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), 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 (Ferguson & Church, 2004; Hallermeier, 1980; Lorenzo-Trueba & Ashton, 2014; Ortiz & Ashton, 2016). (Note that version testing is automated in CASCADE, see link to online repository provided in the Open Research section at the end of this paper.) 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 strategies employed by entities responsible for maintaining coastal roads (herein referred to as roadway barrier management). Cross sections illustrating how the management strategies are implemented in each module through time are shown in Figure 1b. We refer interested readers to the CASCADE GitHub (Anarde et al., 2024b) where management module rules and dynamics are thoroughly described (including pseudo code within the model documentation) are thoroughly documented for ease of reproducibility and use within other model frameworks. 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 (Figure 1b). 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 bay water cells (both determinations are made at the end of a model year before management actions are implemented). Thereafter, we consider the roadway abandoned – meaning all roadway management actions cease indefinitely – 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; see "R" label which demarcates the road location in Figure 1b). The new roadway elevation is then set to the average of the (natural) elevation of the island interior at its new location. Overwashed sand 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 (i.e., there is a 'bulldozer' in our model; Lazarus & Goldstein, 2019). Because the roadway is part of the barrier interior in the model, it is erodible and therefore allowed to scour. (Here, scouring is not just limited to the edge of pavement but can occur along the entire width of the roadway.) 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 at each time step. Consequently, for a given dune design height, dunes are not always rebuilt to the same elevation relative to sea level. 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 nourishing to maintain a wide beach, which maintains communities in a fixed cross-shore position. 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 w_{b_0}, for each barrier segment, based on the user-specified constant beach slope β and berm height h_{berm} from Barrier3D:

$$w_{b_0} = h_{berm} \,/\, \beta \,. \qquad (1)$$

The initial beach width is thereafter modified dynamically by nourishment and shoreface dynamics. Nourishment is triggered by a minimum beach width $w_{b_{min}}$, 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):

$$x_{s2} = x_{s1} - (2 * v_{nourishment}) \,/\, (2 * h_{barrier} + d_{sf}) \,, \qquad (2)$$

where $h_{barrier}$ is the average height of the barrier, d_{sf} is the shoreface depth, and $v_{nourishment}$ is the nourishment volume (in m^3/m). This results in a new shoreline position x_{s2}, shoreface slope, and new beach width w_b (e.g., for the case of the first nourishment, $w_b = w_{b_0} + [x_{s1} - x_{s2}]$). 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 (Figure 1b). Beach width is also modified for erosional shoreface adjustments stemming from SLR as well as alongshore diffusion of sediment. 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 beach 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 rebuilt 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 (Figure 1b). 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 oceanfront 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. (Note, the funneling of flows and overwash that may occur because of residential or commercial structures is not explicitly modeled). Following Rogers et al. (2015), the overwash volume is simply reduced uniformly 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 2. To simulate the return to the littoral system of deposited overwash sand collected from local roads, driveways, parking lots, etc. – which are also not explicitly resolved in the model – we uniformly subtract an additional percentage of the overwash sand volume (here, 9%) and return this volume to the dune; the remaining amount stays in place on the barrier interior.

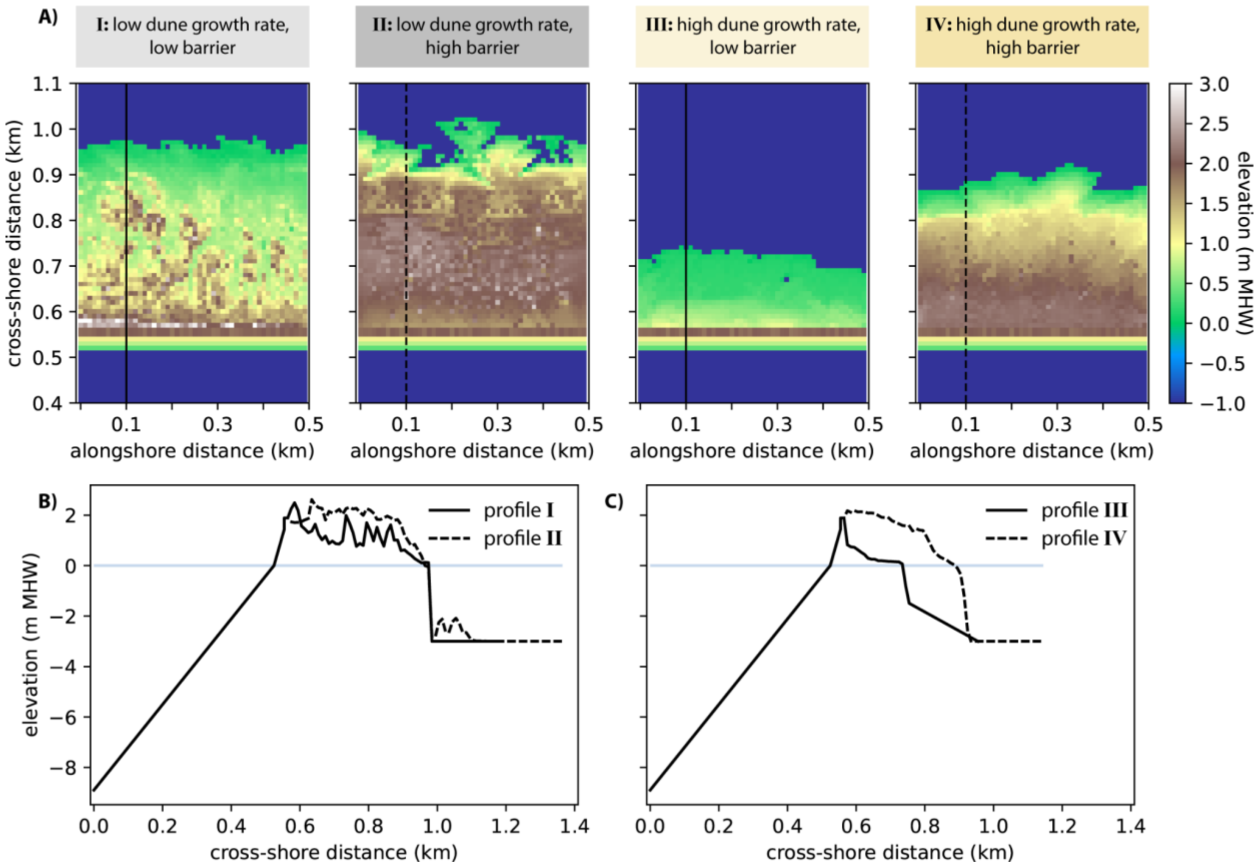

Figure 2. Initial barrier configurations for the management simulations (referenced as configurations I-IV herein) in **a)** planform and **b-c)** sample cross-sectional view (at 0.1 km). A low barrier elevation profile (solid line) and high barrier elevation profile (dashed line) illustrate elevation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

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 decreases 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; Town of Nags Head, 2022).

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 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 33-yr empirical storm record for Hog Island (1980-2013; I. 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, 2019b). 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 $\bar{r}$ (Durán & Moore, 2013; Houser et al., 2015), 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 constant (linear) versus accelerated SLR (see Supplement). Because all four initial barrier configurations can naturally keep pace when SLR is constant at 4 mm/yr (see results of additional 8 mm/yr and 12 mm/yr simulations in Figure S4), we use this linear rate to examine how roadway barrier- and community barrier-management actions in isolation change the physical characteristics of barrier systems over long time scales (here, 1,000 years). This linear rate of 4 mm/yr is slightly lower than the current rate of global mean SLR (4.4. mm/yr; Willis et al., 2023). Importantly, the mean SLR rates in the Southeast, USA are accelerating (>10 mm/yr south of Cape Hatteras, NC since

2010) due to changes in ocean circulation, salinity, and ocean warming (Dangendorf et al., 2023). We explore the dynamics that emerge from more complex scenarios that include acceleration in SLR, as well as changes in storm intensity and frequency, in our companion paper, Anarde et al. (2024a).

Additionally, while CASCADE can simulate the coupling of many barrier segments alongshore through diffusive sediment transport, here we focus only on the dynamics associated with the management of individual barrier segments. Alongshore variability in roadway barrier-management and community barrier-management strategies is examined in the companion paper, Anarde et al. (2024a).

3 Results

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 bay water cells) or the barrier 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.

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 dune design height	4	I, II, III, IV	1 roadway	linear	0 m/yr	3, 4
2-m dune design height	4	I, II, III, IV	1 roadway	linear	0 m/yr	3, 4
3-m dune design height	4	I, II, III, IV	1 roadway	linear	0 m/yr	3, 4
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 + background erosion	4	I, II, III, IV	1 commercial	linear	1 m/yr	5, 6

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 as the barrier becomes too narrow to sustain the practice of relocating the road landward when it becomes threatened by shoreline erosion (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 and thereby enabling the potential landward relocation of the roadway. However, more overwash also causes faster shoreline retreat, potentially leading to barrier 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, and 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 relative to the 3-m dune design-height scenario.

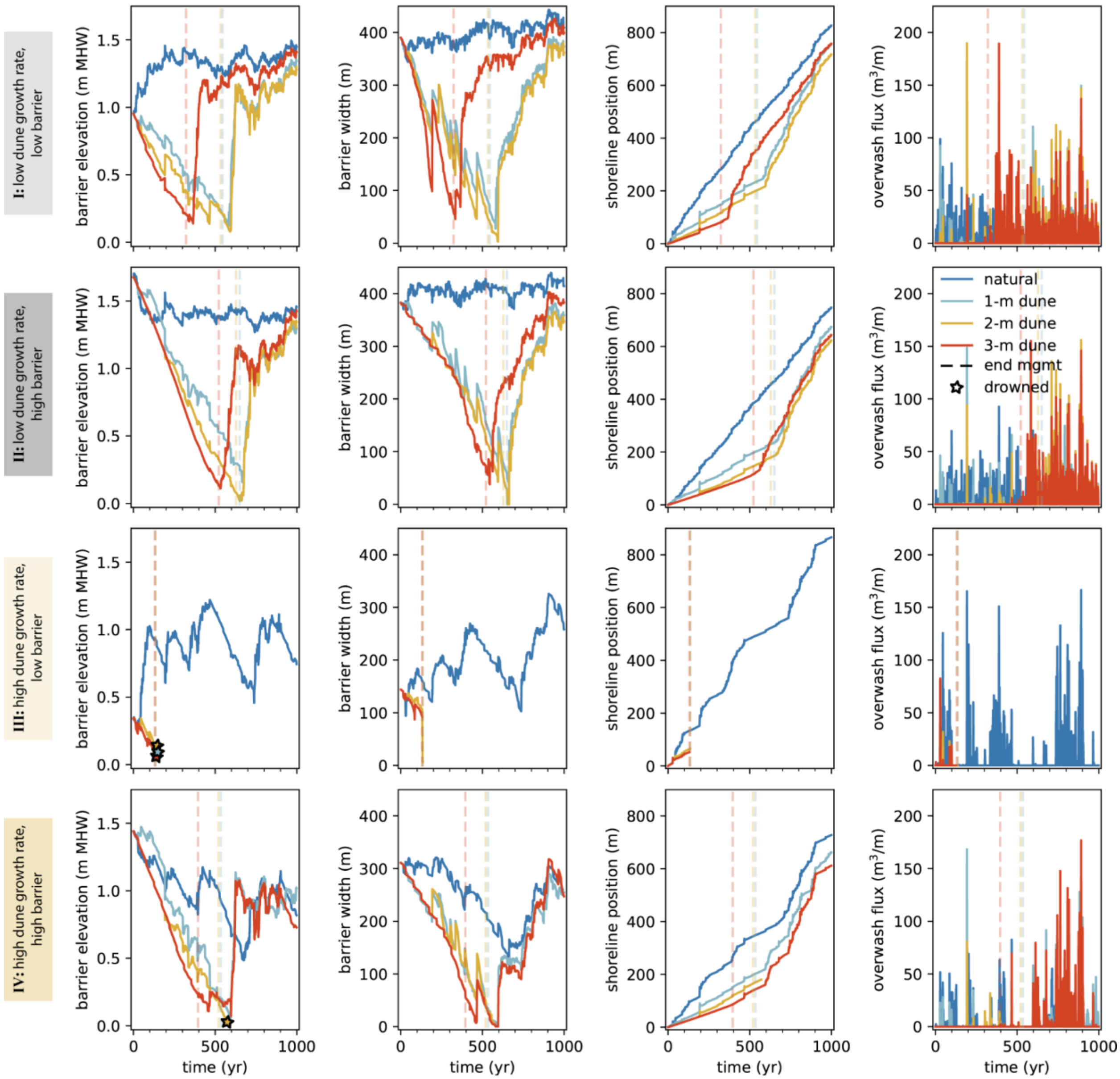

Figure 3. Time evolution of average barrier elevation, average barrier width, shoreline position, and overwash flux (columns) for each roadway barrier-management scenario (dune design heights of 1, 2, and 3 m above the roadway; colors) and initial barrier configuration (rows) with linear SLR (4 mm/yr).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

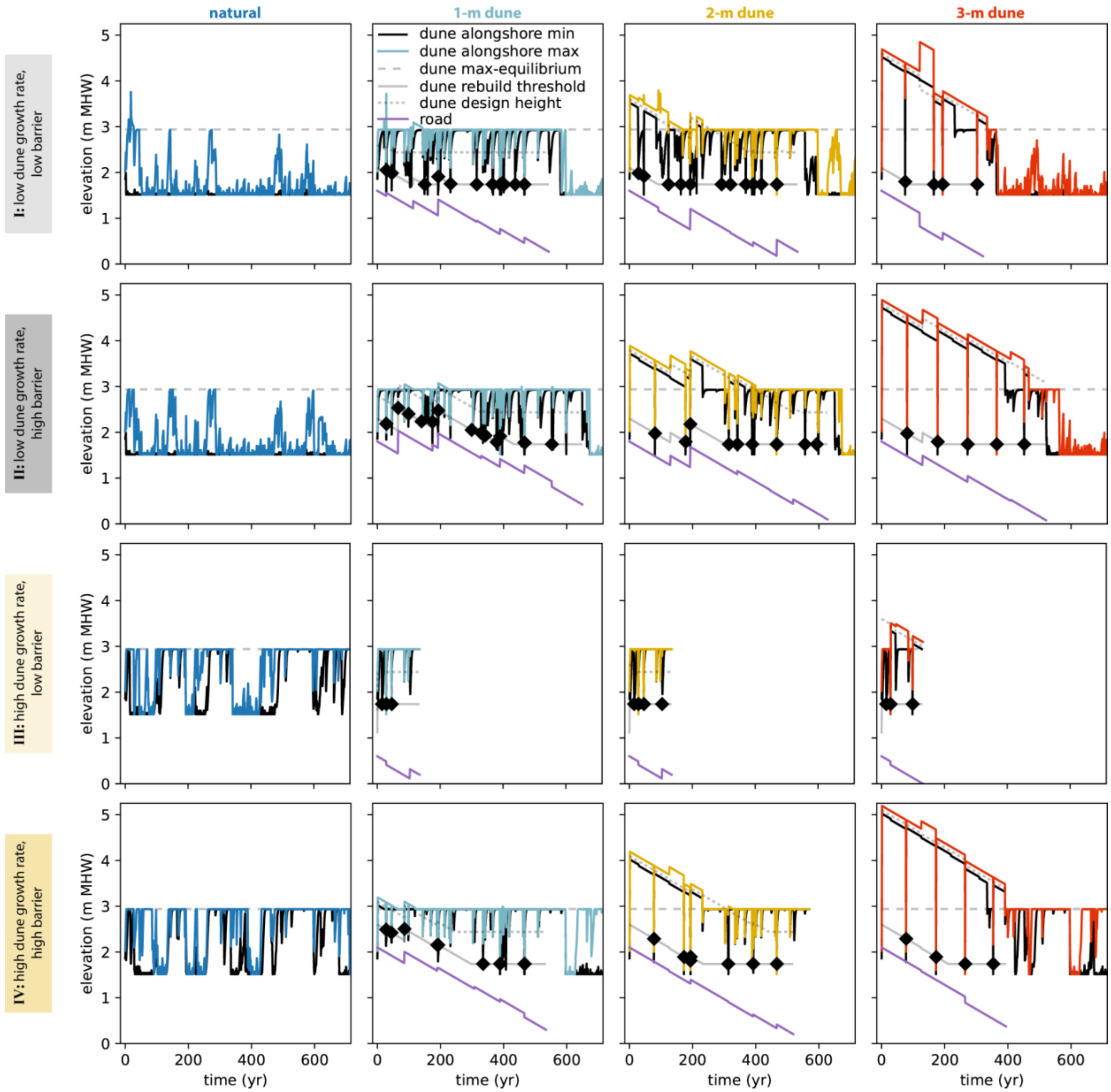

Figure 4. Dune and road elevations over time for each roadway barrier-management scenario (columns, colors) and initial barrier configuration (rows). Dunes are rebuilt when their crest elevation falls below the rebuild threshold (solid gray line), which is relative to the roadway elevation (purple line) 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, randomness 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 barrier 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 barrier 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).

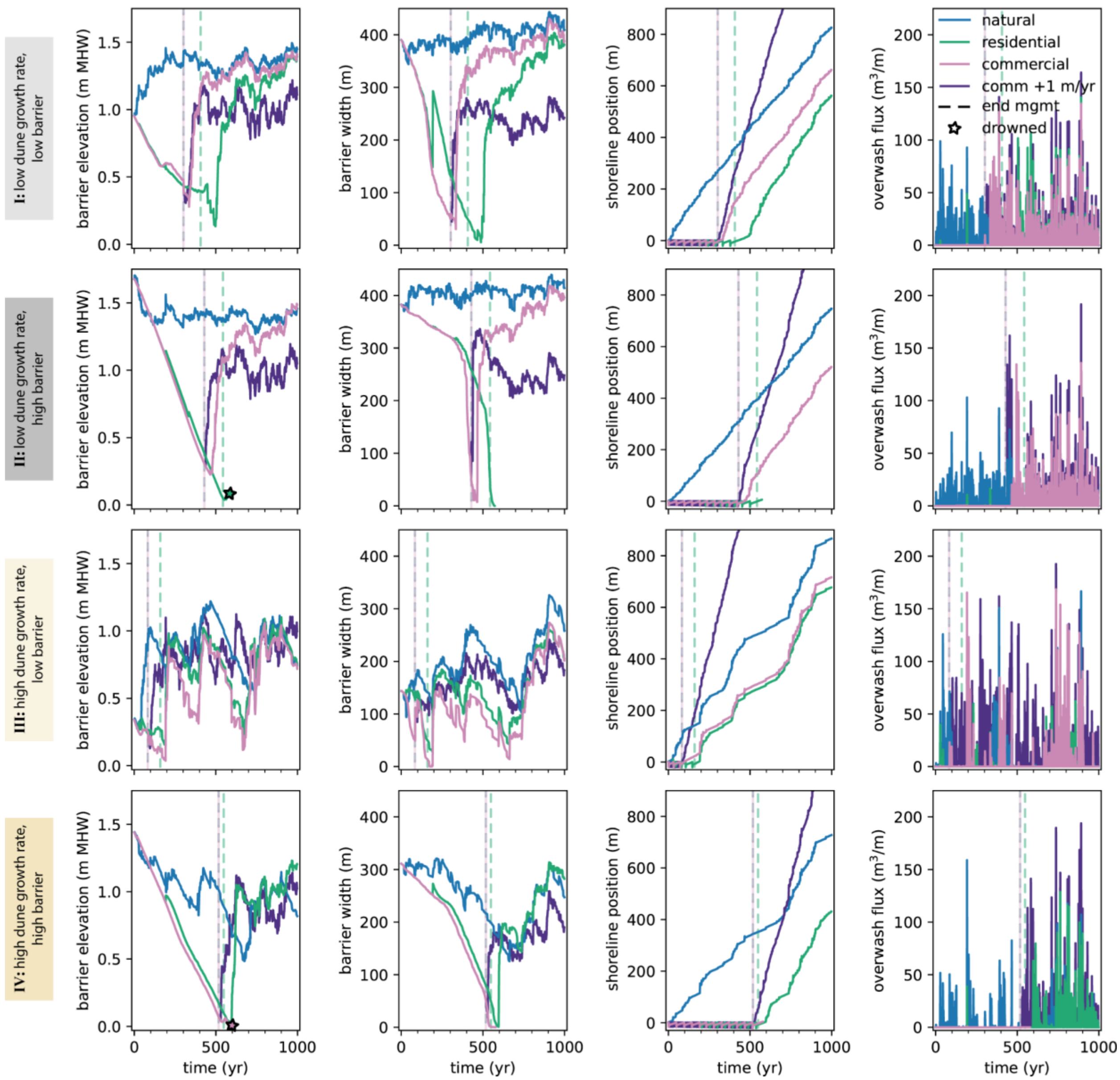

Figure 5. Time evolution of average barrier elevation, average barrier width, shoreline position, and overwash flux (columns) for each community barrier-management scenario (colors) and initial barrier configuration (rows) with linear SLR (4 mm/yr). Scenarios include dune and beach management for a community 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.

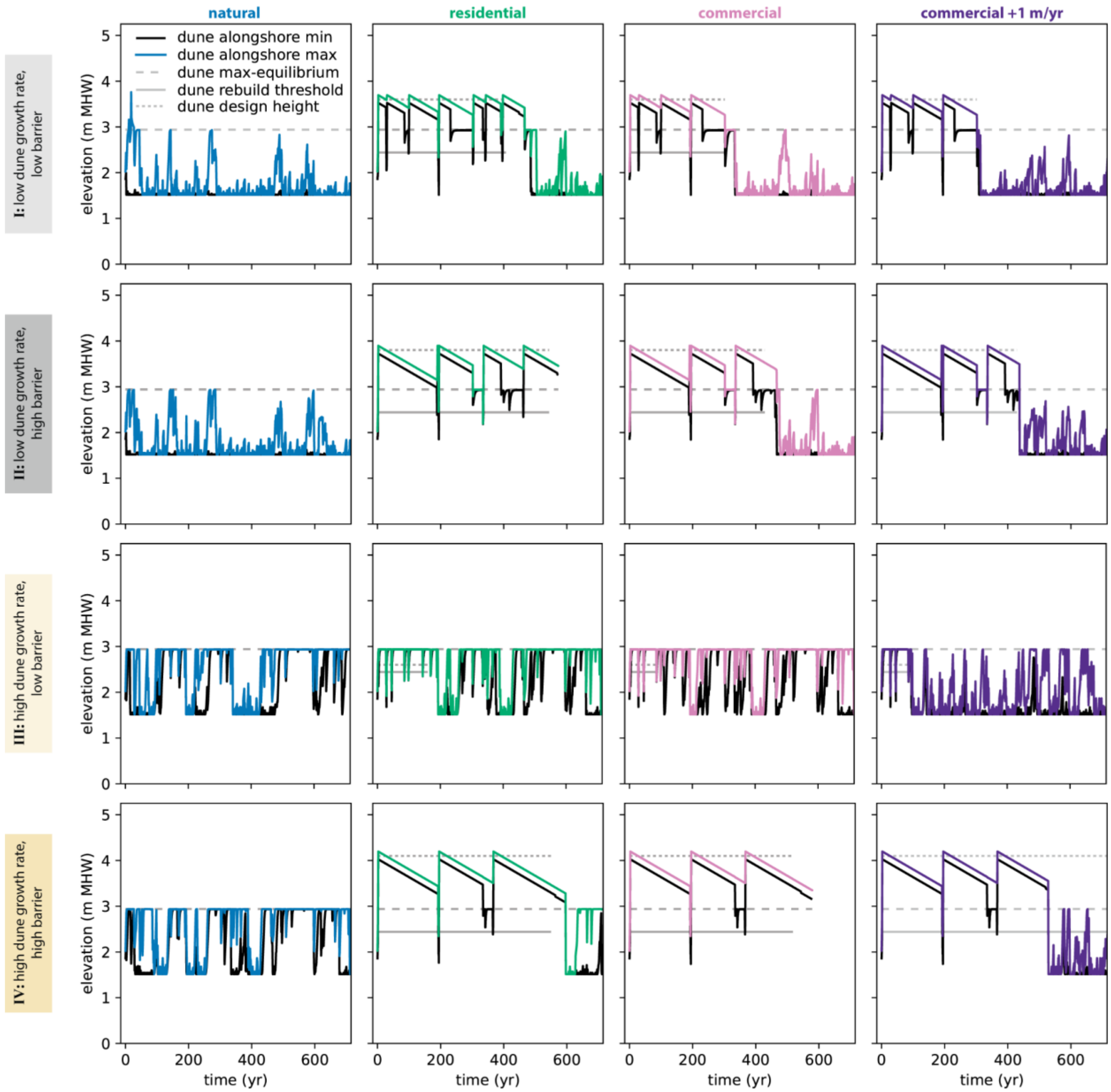

Figure 6. Dune elevation over time for each community barrier-management scenario (columns) and initial barrier configuration (rows). Dunes are rebuilt when their elevation falls below the dune rebuild threshold (solid gray line), which is fixed at 1 m above the berm elevation (1.44 m MHW) for the duration 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 the interior elevation and increases barrier 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, width, and shoreline position by the end of the 1,000-year simulations, approaching the autogenic variability of the natural steady state.

4 Discussion

With the newly developed natural-human-dynamics modeling framework, CASCADE, we provide new understandings of feedbacks between natural processes and human actions that modify coastal landscapes as they unfold over time to alter 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, and iii) 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 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., Magliocca et al., 2011; McNamara & Werner, 2008a,b; 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 and initial conditions.

In the following subsection we discuss some additional processes that could be incorporated into the CASCADE framework, and that might improve the quantitative fidelity of the model. These potential additions, however, would not likely affect the qualitative insights arising from our model experiments, which are intended to be relevant to any developed barrier system involving blocking and filtering of overwash by dunes (especially when managed) and infrastructure. In the final subsection we discuss these insights.

4.1 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 sufficiently high water levels to cause inundation (Sallenger, 2000), which can remove sediment from barriers, and therefore could increase the likelihood of drowning.

4.2 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 (500 m in length, 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 storm 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 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). Therefore, the maintenance of tall dunes limits the capacity of the barrier interior to keep pace with SLR (i.e., reduces its resilience), particularly for the low-lying portions of the barrier adjacent to bay shorelines. Before complete submergence by SLR, these low-lying areas will likely also be subject to flooding outside of storms due to tides and other local factors that contribute to high water levels (wind setup, groundwater, rainfall). Once overcome by SLR, barrier segments with very narrow or mostly 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 Anarde et al. (2024a).

Notably, most individual barrier segments managed for roadways or communities quickly rebound, showing increases in interior elevation and 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. Here, in the community barrier-management scenarios, 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.

In this initial examination of the dynamics of developed barrier systems using the CASCADE modeling framework, to maximize clarity we have focused on relatively simple numerical experiments, each involving a single set of management strategies for roadway barrier management or community barrier management. Each of the simulations are also driven by the same linear SLR rate and the same storm forcing. In a companion paper (Anarde et al., 2024a), we investigate the dynamics and complexities that arise when different management strategies are arrayed along multiple adjoining barrier segments that are linked by alongshore sediment transport. We also explore how accelerations in SLR and increases in storminess affect the frequency at which management interventions are applied, and the pathway to barrier uninhabitability.

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 internal system dynamics (dune management, natural dune growth and recovery rates) and the initial barrier configuration (barrier width and elevation). When dunes are rebuilt to higher elevations (higher dune design height), dune growth rates are higher, and initial barrier geometry is lower (and wider), barriers become uninhabitable sooner. When dunes are rebuilt to lower elevations (lower dune design heights) and dune growth rates are slower, more overwash reaches the barrier interior, which allows barriers to be habitable farther into the future. In this case, more overwash also leads to faster shoreline erosion and more frequent road relocation and nourishment. The degree to which development blocks sand delivery by overwash also affects habitability: blocking of greater amounts of overwash sand (e.g., by commercial properties) causes barriers to become uninhabitable sooner.

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 foredune) 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 barrier 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.

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Open Research

The data on which this article is based is available in Anarde et al. (2023) and Reeves et al. (2022). The CASCADE software is available from Anarde et al. (2024b).

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