The Future of Developed Barrier Systems - Part II: Alongshore Complexities and Emergent Climate Change Dynamics

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Key Points:

- When management strategies vary alongshore, their effects are coupled via alongshore sediment redistribution, influencing barrier evolution
- Beach nourishment (along portions of barriers) induces system-wide lags in shoreline retreat, even decades after nourishment practices cease
- More overwash (due to lower dunes or increased storminess) can prolong habitability, but drives increased nourishment frequency elsewhere

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 for most communities in its current form. Before reaching this state, choices will be made to modify the natural and built environment to reduce relatively short-term risk. These choices will likely vary substantially even along the same developed barrier system as these landscapes are rarely uniformly managed alongshore. Building on the results from a companion paper, here we use a new modeling framework to investigate the complexities in barrier system dynamics that emerge as a function of alongshore variability in management strategies, accelerations in SLR, and changes in storm intensity and frequency. Model results suggest that when connected through alongshore sediment transport, barriers with alongshore variable management strategies – here, the construction of dunes and wide beaches to protect either roadways or communities – evolve differently than they would in the absence of alongshore connections. Shoreline stabilization by communities in one location influences neighboring areas managed solely for roadways, inducing long-term system-wide lags in shoreline retreat. Conversely, when barrier segments managed for roadways are allowed to overwash, this induces shoreline curvature system-wide, thus enhancing erosion on nearby stabilized segments. Feedbacks between dunes, storms, overwash flux, and alongshore sediment transport also affect outcomes of climate adaptation measures. In the case of partial, early abandonment of roadway management, we find that system-wide transitions to less vulnerable landscape states are possible, even under accelerated SLR and increased storminess.

Plain Language Summary

Because humans inhabit barrier islands and spits (collectively referred to as "barriers") these landscapes, that would otherwise naturally change shape in response to storms and sea-level rise (SLR), are influenced by efforts to protect development with wide beaches and tall dunes. These features interfere with a process called overwash, which transports sand landward during storms, building barrier elevation relative to sea level. Here, we use a new model to better understand how these interactions influence the habitability of barriers over time. Our simulations show that different management decisions made for adjacent coastal segments affect each other in positive and negative ways. When communities nourish beaches, adjacent to segments managed for roadways, some nourished sand reaches the adjacent segments, reducing shoreline erosion there. Conversely, portions of barriers that are managed only for roadways allow some overwash to reach the barrier interior; this negatively affects neighboring communities by enhancing their shoreline erosion rates. We find that early abandonment of dune management along portions of barriers may prevent highly vulnerable future states, such as barrier drowning. As communities explore choices for climate adaptation, our findings reveal the importance of coordination among decision makers in adjacent communities to avoid undesirable outcomes.

1 Introduction

Previous work has demonstrated that over long timescales (decades to centuries), developed barrier islands and spits (herein, referred to collectively as "barriers") become narrower and lower with sea-level rise (SLR). This is largely due to the blocking and filtering of overwash by tall dunes and development (Magliocca et al., 2011; McNamara & Werner, 2008a, 2008b; Miselis & Lorenzo-Trueba, 2017), or woody vegetation (Reeves et al., 2022a), as well as the removal of overwash from roadways and other developed areas after storms (Anarde et al., 2024a; Lazarus et al., 2021; Rogers et al., 2015). Overwash – the process by which sand is delivered to the barrier interior by elevated water levels and waves – is a natural land-building process, and is essential for barriers to maintain elevation and width as sea level rises (Leatherman, 1979, 1983; Moore & Murray, 2018). In the short run, human efforts to limit overwash in order to protect infrastructure can be justified by the benefits and services provided by these developed landscapes (Landry and Hindsley, 2011). However, in the long run, these actions will inevitably lead to a barrier state that is too low or too narrow to maintain development in its present form (Anarde et al., 2024a).

How many decades into the future developed barriers will continue to be habitable by humans (i.e., the 'habitability timescale') is largely unknown. This is in part because of uncertainties in exogenous climate factors (e.g., SLR and storms), as well as human factors, including choices about whether or when to adopt management practices or to implement more extreme adaptation measures. As demonstrated by Anarde et al. (2024a), management actions and natural barrier evolution are tightly coupled, and together, influence habitability timescales. For this reason, investigations of the long-term outcomes of near-term mitigation and adaptation decisions are needed to provide insights into how different levers – actions by individuals, communities, governments, or civil society groups (e.g., buyouts, partial or full abandonment of infrastructure), undertaken with the hope of improving long-term resilience – may alter the evolution of barrier communities and landscapes in future decades.

Using the CoAStal Community-lAnDscape Evolution (CASCADE) model, Anarde et al. (2024a) demonstrated that barriers can become uninhabitable within a century after development under some commonly used management strategies. The timescale of habitability was found to depend on the initial geometry of the barrier and the degree to which different management actions – namely 1) dune management to maintain roadways, and 2) beach and dune management to protect communities – allow for overwash delivery to the interior. Importantly, some simulations resulted in barrier drowning after management actions ceased (i.e., after the roadway drowned or the barrier became too narrow to maintain a community), whereas others resulted in a rebound in barrier height and width within decades. Whether a barrier drowned or rebounded was found to be dependent on stochasticity (or randomness) in the timing and intensity of storms and dune recovery processes (herein, referred to as "dune-storm stochasticity").

The simulations of Anarde et al. (2024a) provide general insights into the couplings between human and natural processes that are important to the long-term evolution of developed barrier systems. While the findings apply broadly, the details of each evolutionary pathway are the result of a single climate forcing – namely a 1,000-year storm sequence (with an average of 8 storms per year) and a linear rate of SLR (4 mm/yr). Different exogenous climate forcings are likely to result in differences in modeled timescales of barrier habitability and the probability and timing of barrier drowning. For example, climate-driven changes to wave climate could increase or decrease 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. Likewise, because SLR contributes to shoreline retreat and overwash frequency, accelerations in the rate of SLR (e.g., Dangendorf et al., 2023; Hamlington et al., 2020; IPCC, 2014; Rohling et al., 2013) would likely accelerate shoreline retreat rates (e.g., Anderson et al., 2023; Mariotti & Hein, 2022) and therefore modify dune recovery processes. Cumulatively, changing climate factors are likely to significantly influence the timing of human decisions to modify management practices, and the long-term outcomes of climate adaptation measures in developed barrier systems.

In addition, the simulations of Anarde et al. (2024a) focused only on the dynamics associated with the management of individual (0.5-km long) barrier segments. Human manipulations in barrier systems have been found to modify regional patterns of coastline change due to alongshore sediment transport (Armstrong & Lazarus, 2019; Ells & Murray, 2012; Slott et al., 2010; Williams et al., 2013). Hence, given spatial heterogeneities in beach and dune management strategies, the coupling between adjacent barrier segments that alongshore sediment transport creates likely influences the timescale of habitability in developed barrier systems. To assess this, here, we evaluate the complexities that arise from alongshore couplings when roadway and community barrier-management strategies are carried out in tandem. We also further investigate the dynamics of developed barriers under accelerations in SLR and changes in storm intensity and/or frequency (i.e., increasing 'storminess'). Our analysis focuses on providing insights into processes and dynamics that are most likely to influence the effectiveness of adaptation strategies, and other potential levers to improve long-term outcomes.

2 Methods

2.1 CASCADE

Here, we use the new exploratory model framework CASCADE to simulate the multi-decadal evolution of developed barrier systems. The model dynamics are described in detail in Anarde et al. (2024a); a brief summary of relevant processes is included here.

CASCADE couples elements of two exploratory models – Barrier3D (Reeves et al., 2021) and the BarrierR Inlet Environment (BRIE) model (Nienhuis & Lorenzo-Trueba, 2019a) – into a single geomorphic model of barrier evolution. Within CASCADE, Barrier3D is used to simulate SLR, storm impacts and overwash deposition, dune growth and recovery, shoreline change, and dynamic shoreface evolution for 0.5-km long barrier segments. If a model experiment involves multiple barrier segments (to create a several km-long barrier system), the model employs the diffusive wave-driven sediment transport model of Ashton & Murray (2006) housed in BRIE to connect individual barrier segments. Importantly, the algorithm employs periodic boundary conditions at the outermost boundaries, and the coupling is limited to ocean-side processes (shoreface and shoreline evolution). 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.

Human dynamics in CASCADE are housed within two separate modules: the "roadway barrier-management" module and the "community barrier-management" module. Both modules are inspired by and parameterized for management strategies employed in North Carolina (NC), USA. In the first module, we simulate strategies commonly employed for roadway protection (Douglass et al., 2020; Velasquez-Montoya et al., 2021), including construction of dunes to prevent overwash, maintenance of roadways at a low-elevation to prevent scouring and pavement damage, removal of overwash from roadways, and road relocation into the barrier interior. In the second module, we simulate strategies commonly employed to maintain communities in fixed cross-shore positions, including nourishment of beaches, construction of tall dunes, overwash removal from developed areas, and the blocking and filtering of overwash by development (both residential and commercial). Management actions in each module are triggered based on thresholds (e.g., a minimum dune crest elevation or beach width), and management continues until the barrier is no longer suitable for human habitation (i.e., it becomes too narrow to maintain a community or becomes too narrow to relocate the roadway). After management ceases, we consider the barrier abandoned, and it is thereafter allowed to evolve naturally following the rules of Barrier3D and BRIE. We elaborate on the initial conditions, management thresholds, and abandonment criteria for the simulations detailed in this paper in Section 2.2.

Importantly, individual barrier segments can drown if the barrier interior becomes submerged by SLR. Anarde et al. (2024a) observed drowning to be a potential long-term outcome of coastal management practices, but they also observed drowning under natural forcing alone (i.e., when dunes are caught in a high state and the barrier interior is sufficiently low such that it becomes passively inundated by SLR). Because modern analogs indicate that barriers can reemerge post-drowning, in our simulations, drowning is taken to indicate initial submergence of the barrier interior. CASCADE does not currently simulate processes that may contribute to the return of a drowned barrier segment (submerged shoal) to a subaerial state (e.g., Mariotti 2021), nor processes that may lead to development of a tidal inlet at the location of drowned segments (e.g., Nienhuis & Lorenzo-Trueba, 2019a,b). Therefore, if a barrier segment drowns in CASCADE, the simulation ceases.

In this paper, we examine contributions to developed barrier dynamics from accelerations in SLR and an increase in storminess. Due to the challenges of extending accelerated rates into the distant future (Rohling et al., 2013), our accelerated SLR scenarios are capped at 200 years. As discussed in the Supplement of Anarde et al. (2024a), our accelerated SLR scenarios result 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). Importantly, the accelerated SLR formulation used herein assumes a gradual increase in the rate of SLR (following a sigmoidal formulation; Rohling et al., 2013), and is therefore not representative of the current rapid accelerations in mean sea level that have been observed along the Southeast, USA (>10 mm/yr south of Cape Hatteras, NC, since 2010) stemming from sterodynamic sea level contributions – that is, local changes in ocean circulation, salinity, and ocean warming (Dangendorf et al., 2023). We compare simulations including accelerated SLR to simulations that include linear SLR, using a linear rate of 4 mm/yr, as in Anarde et al. (2024a). This linear rate is slightly lower than the current global rate of mean SLR (4.4 mm/yr; Willis et al., 2023); at this rate, individual barrier segments can keep pace with SLR throughout the model simulations. (See the Supplement of Anarde et al. (2024a) for an analysis of how outcomes vary with different linear rates of 4, 8, 12 mm/yr and accelerated rates of SLR under natural conditions, for each initial barrier geometry.)

To investigate the impacts of an increase in storminess – including an increase in annual overwash fluxes due to changes in frequency and/or intensity of storms – we follow the methodology of Reeves et al. (2021) and generate new storms from the default 10,000 synthetic storms used in Anarde et al. (2024a). (The synthetic storms were generated using the multivariate sea-storm model of Wahl et al., (2016), which utilized a 35-yr empirical storm record for Hog Island, Virginia (Reeves et al., 2022b)). To model an increase in storm intensity, we shift 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 synthetic storms. We then increase the average number of storms per year from eight (the default, as used by Anarde et al. 2024a) to 12.

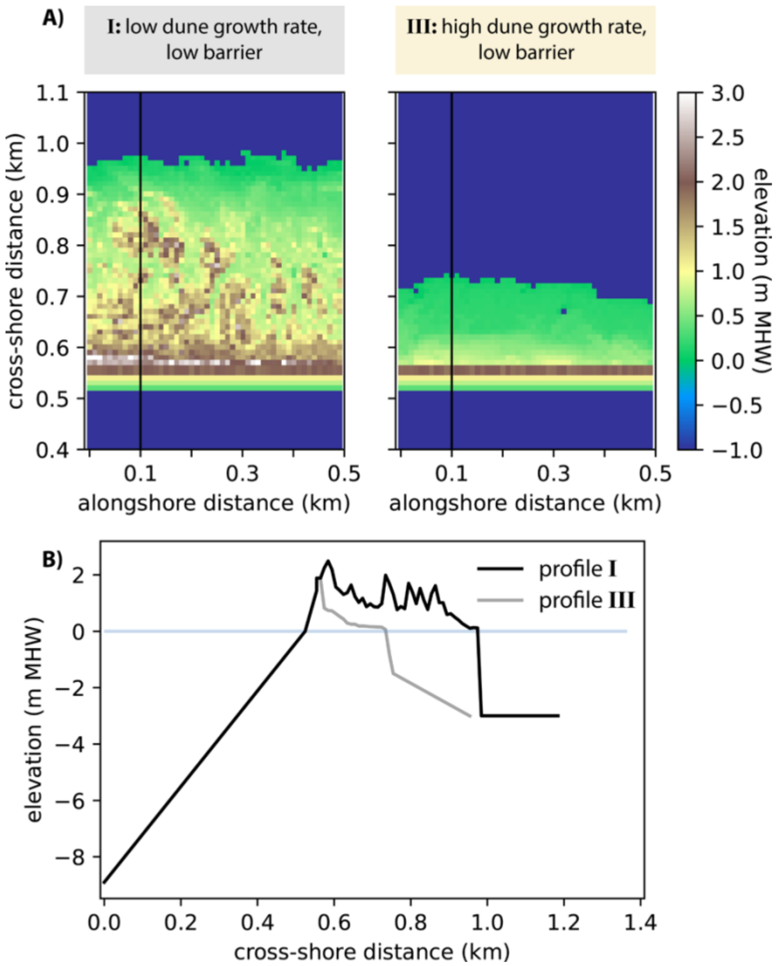

Figure 1. Initial barrier configurations for the management simulations in **a)** planform and **b)** sample cross-sectional view (at 0.1 km). Here, we utilize two of the four initial barrier configurations used by Anarde et al. (2024a) – the lowest and narrowest initial barrier configuration (configuration III: high dune growth rate, low initial barrier) and a slightly higher and wider initial barrier configuration (configuration I: low dune growth rate, low initial barrier) – and for consistency with Anarde et al. (2024a), we refer to these initial barrier configurations as III and I herein. A low barrier elevation profile (solid line) and high barrier elevation profile (dashed line) illustrate elevation differences.

2.2 Initial conditions, management thresholds, and abandonment criteria

Anarde et al. (2024a) showed that the time it takes for a barrier to become uninhabitable is sensitive to barrier geometry (elevation and width) at the time of development. Anarde et al. (2024a) also found that after management practices cease, whether a barrier rebounds or drowns depends on the randomness of a storm occurring with an intensity large enough to overtop a dune during its recovery process (i.e, dune-storm stochasticity), which is a function of the natural dune growth rate. In this paper, we initialize the model simulations with two of the four initial barrier configurations used in Anarde et al. (2024a), which vary both in geometry and natural dune growth rate: namely, the lowest and narrowest initial barrier configuration (configuration III: high dune growth rate, low initial barrier) and a slightly higher and wider initial barrier configuration (configuration I: low dune growth rate, low initial barrier). For consistency with the companion paper Anarde et al. (2024a), we refer to these initial barrier configurations as I and III herein (Figure 1).

The range of dune management parameters simulated herein are designed to be representative of strategies employed along the NC (USA) coast. The roadway barrier-management strategies are parameterized for NC Highway 12 (NC-12), a roadway that is vulnerable to storm overwash and shoreline erosion along the NC Outer Banks, USA. As in Anarde et al. (2024a), dunes are rebuilt when the dune elevation falls below 0.5 m above the roadway. Dunes are rebuilt to a height relative to the roadway elevation: here, 2-m above the roadway. As in Anarde et al. (2024a), when the dune migrates onto the roadway the road is relocated to a fixed setback distance of 20 m. We allow roadways to be relocated along individual (0.5-km long) barrier segments, which can induce offsets in roadway position relative to adjacent barrier segments.

The parameters for community barrier management used here are the same as those in Anarde et al. (2024a), which represent management strategies employed in Nags Head, NC, USA. For ease of comparison between the two barrier management modules, dunes in the community barrier-management simulations are always rebuilt to an elevation equal to the initial elevation of the dune line in the roadway barrier-management simulations. In this way, dunes are rebuilt to the same elevation to protect oceanfront homes in place (as opposed to roadways, which tend to decrease in elevation relative to sea level with each rebuild). In this paper, we limit our examination of the overwash filtering effect by development to commercial properties; this involves reducing the overwash volume delivered to the barrier interior by 90% (Rogers et al., 2015). To best simulate large-scale (several km) nourishment practices, nourishment is triggered when the beach width w_b in all community barrier segments falls below a beach width threshold $w_{b_{min}}$ of 30 m. Because Barrier3D does not resolve beach dynamics, the initial beach width w_{b_0} is initialized based on the user-specified constant beach slope and berm height from Barrier3D, and then modified dynamically by nourishment and shoreface adjustments (e.g., for the case of the first nourishment, $w_b = w_{b_0} + \Delta x$, where Δx is the change in shoreline position due to nourishment). Hence, in the model, beach width is a management variable that ensures that the shoreline position stays seaward of the dune line.

The abandonment criteria for both roadway barrier management and community barrier management are the same as that used in Anarde et al. (2024a). For roadway barrier management, an 'uninhabitable state' occurs when 20% of the roadway touches water cells (i.e., the barrier interior is too low) or when the barrier interior narrows to the point that the road cannot be relocated if needed (i.e., <40-m wide). 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. For community barrier management, the barrier is deemed uninhabitable when the barrier narrows beyond 50-m in width, which is equivalent to the combined footprint of a home and roadway.

2.3 Scenario Development

Model parameters and management scenarios for simulations examined herein are summarized in Table 1. All model simulations include a background erosion rate of 1 m/yr and run for 200 years (i.e., the length limit for simulations using accelerated SLR in the CASCADE model). The remaining initial conditions in Barrier3D and BRIE are the same as that used in Anarde et al. (2024a). This includes a 20 m dune line (i.e., 2 cells wide), a natural equilibrium dune crest elevation of 3.4 m NAVD88, berm elevation of 1.9 m NAVD88, mean high water (MHW) of 0.46 m NAVD88, bay depth of 3 m, deepwater wave height of 1 m, and a 7-sec wave period. All elevations reported herein are relative to the MHW datum.

Table 1. Model parameters for each 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 (i.e., each simulation uses a different storm time series; see Table 2).

Scenarios	# of model simulations	Initial barrier configuration	# of barrier segments	SLR	Background erosion rate	Relevant figures
Baseline management scenarios (Section 3.1)						
Roadway barrier management: *2-m design height + background erosion*	1	III	6 roadway	linear	1 m/yr	4
Community barrier management: *commercial overwash filtering + background erosion*	2	I, III	6 commercial	linear	1 m/yr	4
Roadway + community barrier-management scenarios (Section 3.1)						
alongshore-uniform initial configuration, linear SLR	1	III	3 commercial, 3 roadway	linear	1 m/yr	2, 4
alongshore-uniform initial configuration, accelerated SLR	1	III		acc.	1 m/yr	2, 4
alongshore-varying initial configuration, linear SLR	1	III & I		linear	1 m/yr	2, 4
alongshore-varying initial configuration, accelerated SLR	1	III & I		acc.	1 m/yr	3, 4, 7
Increased alongshore complexity scenarios (Section 3.2)						
status quo, linear SLR	1	III & I & III	3 commercial, 3 roadway, 3 roadway	linear	1 m/yr	5
status quo, accelerated SLR	1*	III & I & III		acc.	1 m/yr	5, 7
preemptive road removal, accelerated SLR	1*	III & I & III		acc.	1 m/yr	6, 7
Increased storminess scenarios (Section 3.3)						
status quo, accelerated SLR, increased storminess	100	III & I & III	3 commercial, 3 roadway, 3 roadway	acc.	1 m/yr	Table 2
preemptive road removal, accelerated SLR, increased storminess	100	III & I & III		acc.	1 m/yr	Table 2

In the next section, model results are presented in order of increasing management complexity. We first 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. These scenarios are referred to as "roadway+community barrier management" scenarios. These scenarios are compared to "baseline" simulations 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; Table 1).

We then examine scenarios of "increased alongshore complexity" (Table 1). For the "status quo" scenarios, we simulate a barrier system initialized with low, narrow vulnerable roadway segments bracketed on either side by barrier segments that are higher and wider and differ in management strategies (community to the left and roadway to the right). The status quo scenarios are run for both linear SLR and accelerated SLR (one simulation each). These scenarios are motivated by management strategies employed near the community of Rodanthe, NC, USA (described in more detail in Section 3.2), which are representative of strategies applied on developed barrier coastlines globally and thus extend the applicability of our results more universally. Rodanthe 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 in this location because the barrier is too narrow. The abandoned road segment was replaced with a back-barrier bridge that bypasses the vulnerable barrier segments (NCDOT, 2022).

In an additional scenario, we examine the effects of a potential climate adaptation measure for developed barrier systems with highly vulnerable barrier segments: partial, preemptive abandonment of roadway management practices long before the barrier is deemed unable to support a roadway (referred to as the "preemptive road removal" scenario; Table 1). A final pair of scenarios allows us to assess the effectiveness of current management practices (status quo) and preemptive road removal under conditions of increased storminess (referred to as the "increased storminess" scenarios; Table 1). Results from this scenario are compared to the status quo scenario with increased storminess (the "status quo, increased storminess" scenario).

3 Results

3.1 Roadway+community barrier-management scenarios

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 2). 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 3).

3.1.1 *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 2). 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 2a-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 into the simulation; 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 2d,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 2e). Although it may seem unnecessary to maintain a roadway after a community has been abandoned, we assume here that access to the barrier is still desirable.

3.1.2 *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 3a,b) and accelerated SLR scenarios (Figure 3c-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 3b). 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 3e). The shoreline at drowning is nearly straight because the community segments transgress quickly after abandonment, approaching the shoreline position of the roadway segments.

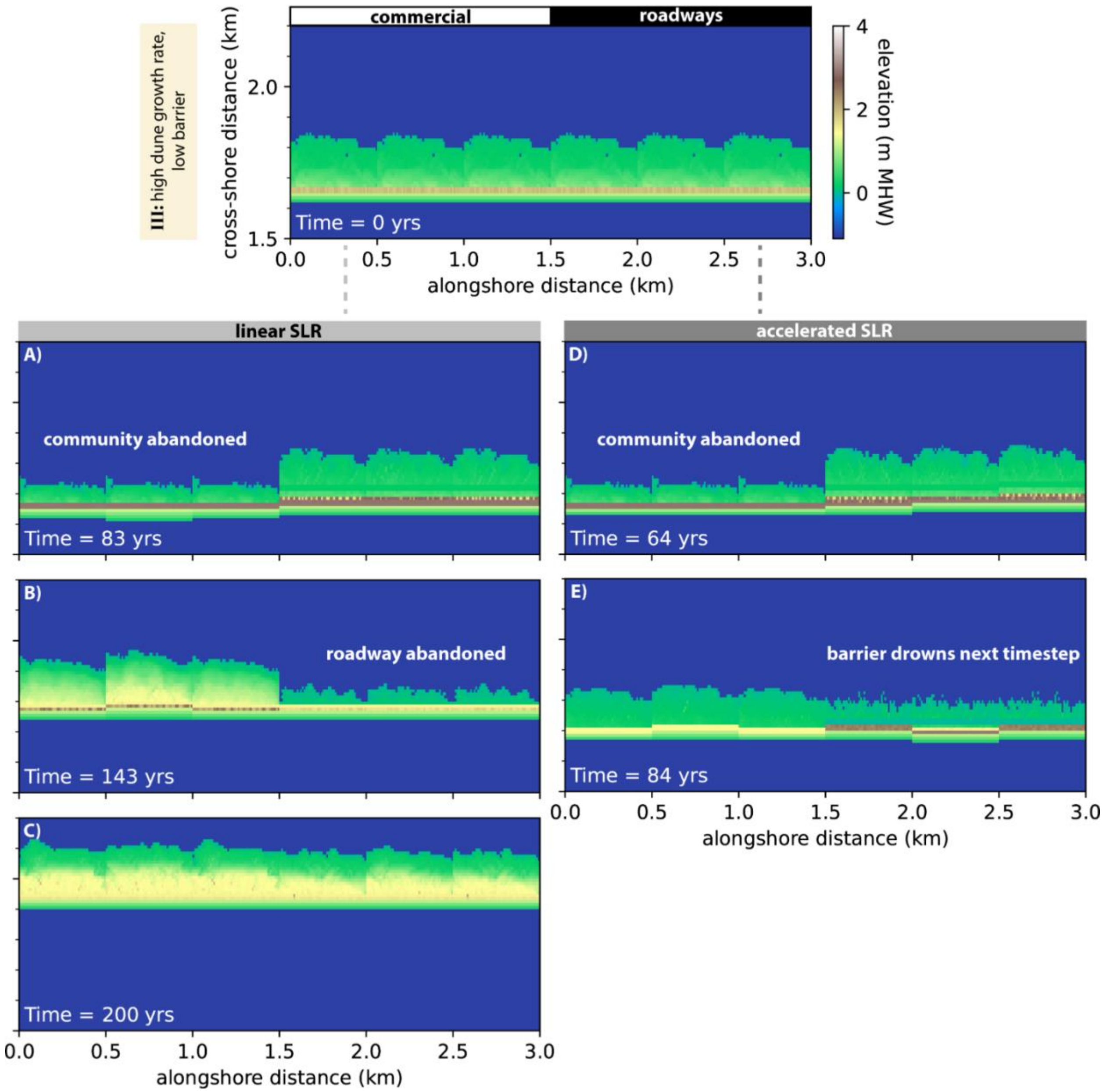

Figure 2. Planform evolution of the roadway+community barrier-management, alongshore-uniform initial configuration scenarios for **a-c**) linear SLR (4 mm/yr) and **d-e**) accelerated SLR, where a low and narrow barrier system is managed for a community on the left half of the domain (0-1.5 km) and managed 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**).

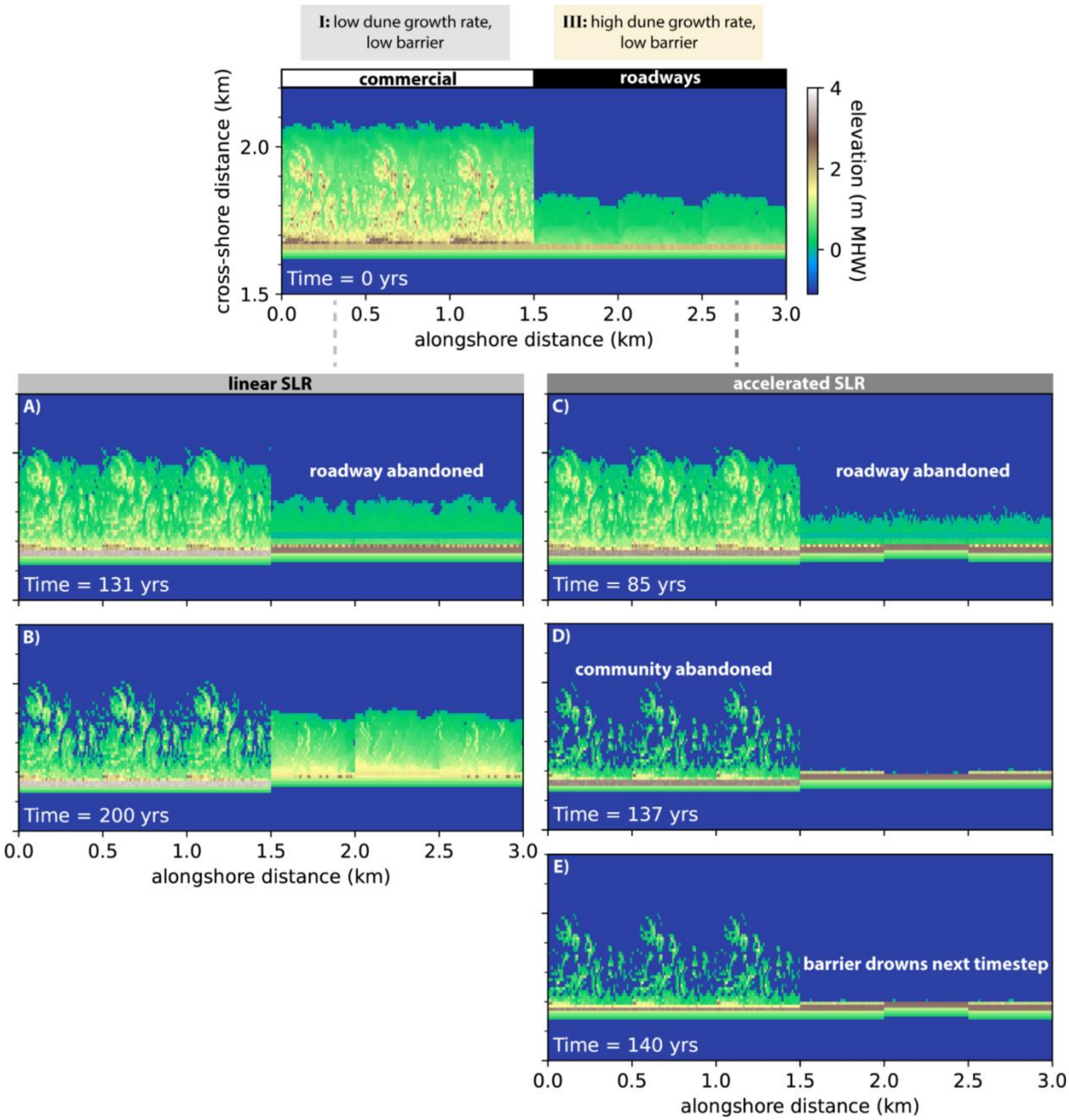

Figure 3. Planform evolution of the roadway+community barrier-management, alongshore-varying initial configuration scenarios for **a-b**) linear SLR (4 mm/yr) and **c-e**) accelerated SLR, where a higher and wider barrier system is managed for a community on the left half of the domain (0-1.5 km) and 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**).

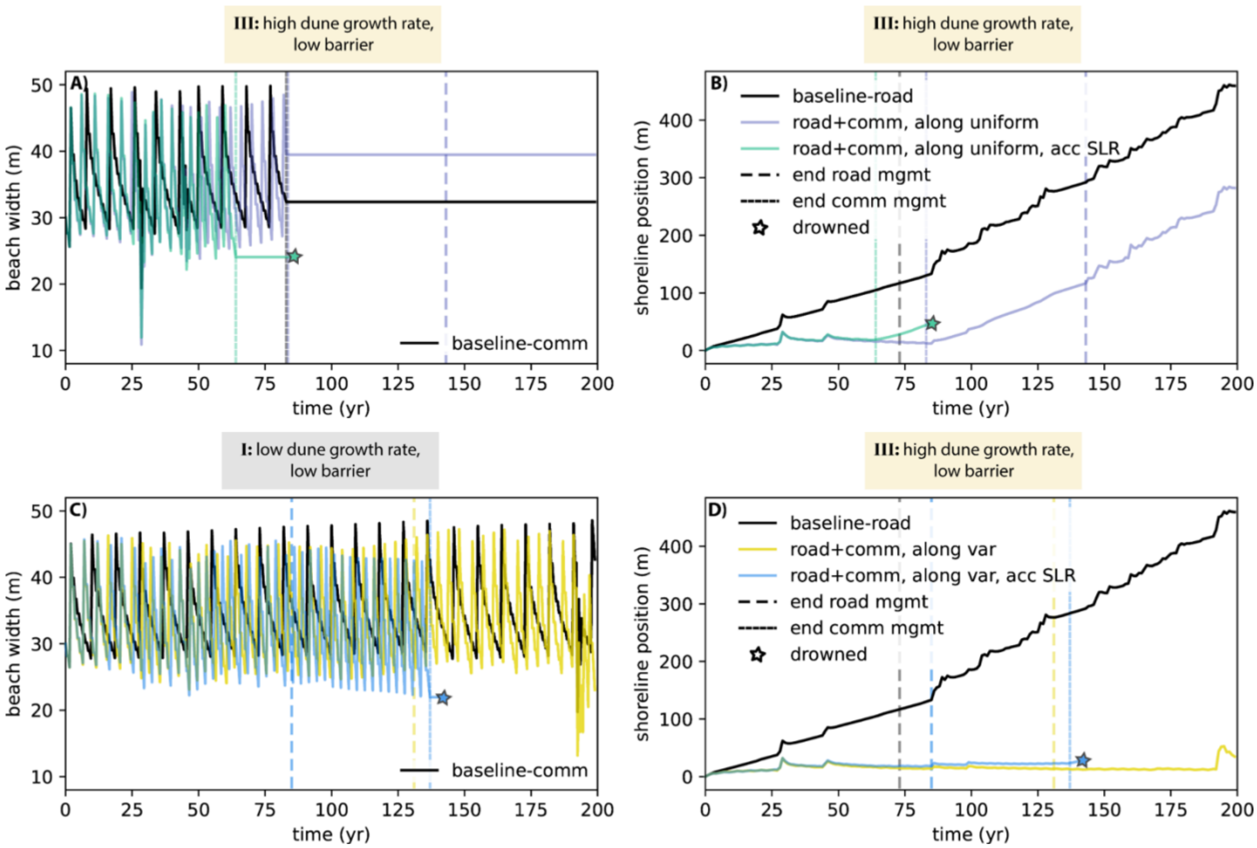

Figure 4. Time evolution of beach width and shoreline position for the middle barrier segment in the community (**a,c**: 0.5-1 km) and roadway management blocks (**b,d**: 2-2.5 km) from the roadway+community management scenarios for **a-b**) linear SLR and **c-d**) accelerated SLR (as shown in Figure 2a,b and Figure 3c,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.

3.1.3 *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 4a-b relates to Figure 2 and Figure 4c-d relates to Figure 3). The black lines in Figure 4 correspond to the "baseline" community or roadway barrier-management scenario for each initial barrier configuration (i.e., a 3-km simulation with no alongshore variability in management and linear SLR; see Table 1).

In Figure 4b, 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 4a).

Similarly, for the case shown in Figure 4c – 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 4d). 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 4d), which results in a need for more nourishment to maintain the specified 30-m beach width in front of the community (Figure 4c). For scenarios with accelerated SLR, the frequency of beach nourishment increases through time to keep pace with sea level.

3.2 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 3. The resulting increased alongshore complexity scenarios introduced below are motivated by a formerly vulnerable stretch of roadway (NC-12) that spanned a wildlife refuge (managed for roadways) and a community (Rodanthe, NC, USA) until the roadway was abandoned in 2022 due to an inability to relocate it landward (barrier interior was too narrow). The roadway along these barrier segments was removed and replaced with a back-barrier bridge.

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. We run simulations for linear SLR (Figure 5a-b) and accelerated SLR (Figure 5c) and refer to these two scenarios as the "status quo" scenarios because we assume (as before) that roadway and community managers will continue to 'hold the line' by maintaining the roadway, or protecting oceanfront homes via nourishment until the barrier narrows and lowers to the critical threshold.

In an additional scenario, we explore 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 (Figure 6). This is analogous to what could be considered preemptive abandonment of roadway management long before the island narrows to the point that road relocation is no longer possible, and thus we refer to this as the "preemptive road removal" scenario. The preemptive road removal scenario is only run for accelerated SLR.

For both the status quo scenario and the preemptive road removal scenario with accelerated SLR, we run an additional 100 simulations to consider the effects of stochastic timing of intense storms (Table 2).

3.2.1 *Status quo scenarios*

Comparing the planform evolution of the barriers in the alongshore-variable initial configuration scenarios (Figure 3) and status quo scenarios (Figure 5) 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 (at the outermost boundaries), 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 7b.

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 5a) than it is in the alongshore-variable initial configuration scenario (131 years, Figure 3a). 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 5b-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 3c-e), representing a factor of 2 decrease.

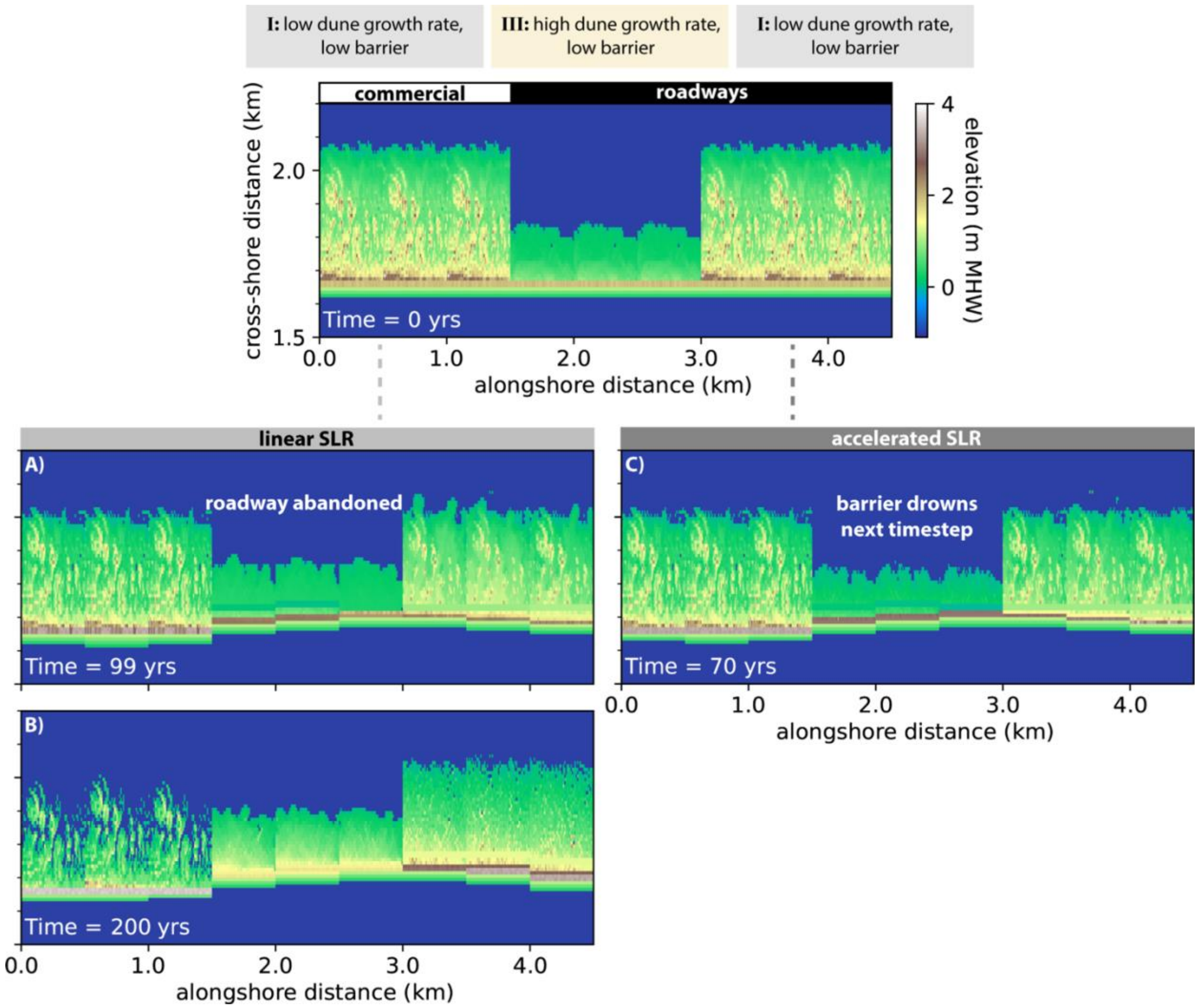

Figure 5. Planform evolution of the increased alongshore complexity, status quo scenarios for **a-b**) linear SLR (4 mm/yr) and **c**) accelerated SLR, where three additional barrier segments (3-4.5 km), all managed for roadways (2-m dune design height), are added to the right side of the domain used 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**).

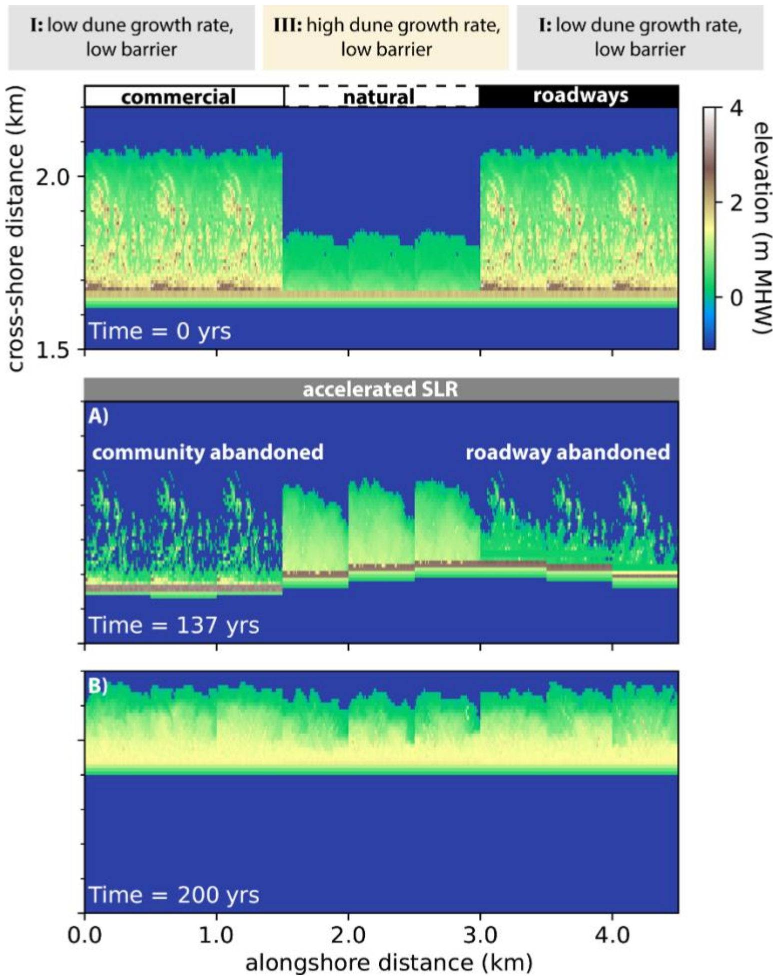

Figure 6. Planform evolution of the increased alongshore complexity, preemptive road removal scenario where the most low-lying and narrow barrier segment is allowed to evolve naturally – analogous to preemptive abandonment of the vulnerable roadway in the middle (three segments) of the domain in Figure 5 (from 1.5 - 3 km) decades before relocation is no longer possible due to barrier narrowing – 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.

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 7a). This occurs because with twice the length of roadway segments in the domain, sediment is redistributed more rapidly out of the community segment (similar to the results in Slott et al., 2008) and into the overwashing roadway segments.

3.2.2 *Preemptive road removal scenario*

Here, 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 relocation is no longer possible due to barrier narrowing – the neighboring community and roadway segments can both be managed for 137 years (Figure 6a), whereas in the status quo scenario (accelerated SLR), the middle roadway segments drowned at 71 years while they were still being managed (Figure 7b). 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 7a) because the unmanaged (low, narrow) barrier segment is overwashed more frequently and therefore moves landward more rapidly.

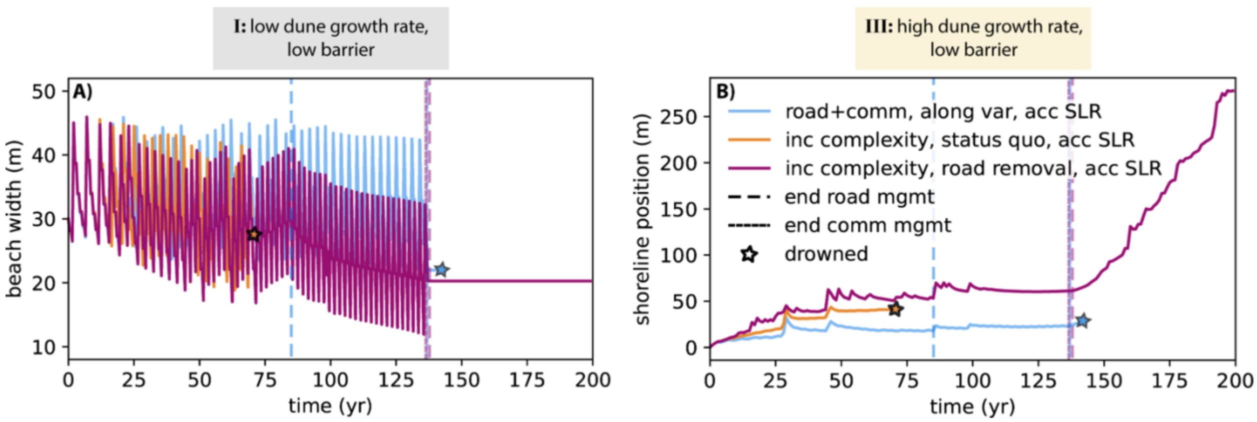

Figure 7. Time evolution of **a)** beach width (reported for a community segment) and **b)** shoreline position (reported for a roadway segment) for the increased alongshore complexity, status quo, accelerated SLR scenario (shown in Figure 5C) and the preemptive road removal scenario (shown in Figure 6; also 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 3c-e). The fine (coarse) dashed vertical lines delineate when community (roadway) management ceased for each simulation; stars indicate barrier drowning.

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 6b and Figure 7b). For each of the other accelerated SLR scenarios explored above, a portion of the barrier system drowns either while management is ongoing (Figure 2e, Figure 5c) or after management ceases (Figure 3e) 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 at 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.

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., 2022b) with the same average number of storms per year (8, see Methods). Table 2 shows that for 100 simulations, drowning occurs 81% of the time for the status quo scenario (with accelerated SLR), 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 occurs later (127 years). Hence, this adaptation measure results in a reduced likelihood of barrier drowning 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 removal of the road (137 years for both increased alongshore complexity scenarios, Table 2) and the timing of roadway abandonment on the 3-4.5 km-long 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 5C; 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; the increased storminess scenarios). 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
status quo, 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
preemptive road removal, *increased storminess*	20	135	144	156	123	135	138	2.06	--	--	--	110	158	193

3.3 Increased storminess scenarios

We simulate the effects of an increase in storminess for the same increased alongshore complexity scenarios described above (status quo and preemptive road removal, both with accelerated SLR) using 100 new storm sequences indicative of a climate with more frequent intense storms (see Methods). 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%) because overwash occurs more frequently allowing for recovery from vulnerable, low-lying states. For roadway segments, where the overwash flux primarily occurs, increased overwash delays the average timing of roadway abandonment (e.g., from 57 to 81 years for the middle roadway segment). The timescale of community habitability is (on average) relatively unaffected by increases in storminess because overwash is extremely limited in this scenario by community development, and any increase in overwash flux is countered by overwash removal and an increase in nourishment frequency. 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%), a delay in the average timing of roadway abandonment (from 125 years to 158 years), and limited changes to community habitability.

Although community habitability as we have defined it is not affected by increased storminess, habitability could be defined differently. If we consider that most communities require a roadway for access, then the time period of habitability could be considered to come to an end when the roadway that provides access can no longer be maintained. In this case, the tendency for increased storminess to delay roadway abandonment indirectly provides a benefit to communities and may effectively extend community habitability where roadway access is essential.

4 Discussion

In a companion paper, Anarde et al. (2024a) showed that management actions taken to protect barrier communities and roadways from storms and the chronic effects of SLR, over decades to centuries, inadvertently reduce the timescale of barrier habitability. This occurs primarily because dune construction prevents overwash from reaching the barrier interior, ultimately leading to the lowering and narrowing of barriers as sea level rises. (Simulations also demonstrated that, by preventing overwash delivery to barrier interiors, development has a similar effect, with higher percentages of overwash blocking leading to shorter habitability timescales.) Overall, Anarde et al. (2024a) found that modeled evolutionary pathways are sensitive to dune management practices (i.e., the height to which dunes are rebuilt), stochasticity in dune-storm interactions (i.e., the potential for a storm to occur before dunes have recovered from the previous storm recovery processes), and initial barrier geometry (i.e., initial height and width). Importantly, to allow a focus on the identification of key system dynamics, model simulations included a linear sea level rise rate, a single storm sequence, and individual (0.5-km long) barrier segments managed to protect either roadways or communities.

Here, we provide new understandings of dynamics that emerge when there are alongshore heterogeneities in beach and dune management strategies. Given the simplified and synthesized nature of our model parameterizations, and by simulating across broad ranges of key input values, our experiments are designed to be relevant to managed barrier communities in general. Again, we find that dune dynamics, storms, and overwash flux exert important controls on patterns of barrier evolution, but couplings between them arise from the effects of alongshore sediment transport. Over decades to centuries, alongshore connectivity of managed barriers can produce complex shoreline shapes, modify dune-storm interactions and therefore overwash flux, and influence the occurrence of barrier drowning. Because barrier drowning is a function of dune-storm stochasticity, when evaluating potential outcomes of climate adaptation measures we simulate many storm sequences to account for uncertainties in future climate forcing. Counterintuitively, we find that increased storminess can positively affect the long-term habitability of barrier systems and influence the outcomes of potential adaptation measures by influencing couplings between dunes, storms, overwash flux, and alongshore sediment transport processes. However, positive effects on long-term habitability (meaning a longer period of sufficiently wide or high landscape) would, of course, tend to be in tension with concomitant increases in storm impacts on communities and infrastructure when storms occur.

4.1 Alongshore complexities

Developed barrier coastlines are rarely managed homogeneously over length scales of tens of kilometers. We find here, by connecting adjacent barrier segments, 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 4b). When connected to adjacent communities that are nourishing, shoreline positions in 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 more frequently overwashed and transgress landward. The increased curvature results in larger gradients in alongshore sediment fluxes. These gradients tend to redistribute sediment into the overwashing segments, which requires adjacent communities to nourish more frequently (Figure 4c after 193 years). For the increased alongshore complexity, status quo scenarios (Figure 5), 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 3). Generally, given the periodic boundary conditions of CASCADE (at the outermost boundaries), as the distance between stabilized community segments in the model increases, shoreline erosion rates for the segments in between the stabilized segments increases, introducing more curvature in the barrier system and a need for more frequent nourishment in the stabilized community segments.

The interactions described above between different barrier segments depend only on the tendency for gradients in alongshore transport to smooth the coastline (i.e., shoreline 'diffusivity') and are independent of the existence or magnitude of net alongshore sediment transport (Ashton & Murray, 2006; Slott et al., 2008; Lauzon et al., 2019). Nourished barrier segments tend to stabilize shorelines 'updrift' as much as 'downdrift', even on coasts with a net alongshore transport, and this stabilization occurs not strictly through spreading of nourishment sediment, but more fundamentally because of gradients in alongshore sediment transport related to shoreline curvatures (Ashton & Murray, 2006; Slott et al., 2008; Lauzon et al., 2019).

4.2 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 can no longer be maintained (Figures 6-7), motivated by a 3-km bridge built landward of the barrier north of Rodanthe, NC, USA in 2022 – we found that the sequence of barrier-system states 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 6a) 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 timescale of community habitability, which is principally governed by the rate of SLR. Hence, communities are affected by increased storminess primarily through an increase in nourishment frequency (and also by the longer presence of a roadway). Overall, we find that enhanced storminess can, under some circumstances, positively affect the habitability of barrier systems (by generating more overwash, which allows 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 barrier interior and remain there and 2) that communities can continue to afford to nourish at the frequency required to 'hold the line'.

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 it will be critical to consider the effects of interactions between dune dynamics and storm overwash potential, alongshore influences of heterogeneous management strategies, and long-time-scale dynamics, when assessing which management practices are likely to enhance, or inadvertently reduce, resilience and habitability. Given the importance of dune-storm stochasticity to the occurrence and timing of barrier drowning, assessing the range of potential long-term outcomes of adaptation measures will require simulating many storm sequences for different projections of SLR and storminess to capture variability.

4.4 Model limitations

Although CASCADE represents management decisions, the influence of economic drivers, and feedbacks between coastal economies and the geomorphic evolution of barriers (i.e., economic-geomorphic feedbacks), are not yet included in the CASCADE framework. Economic drivers and economic-geomorphic feedbacks are important at the community scale because they will influence the selection of, and the effectiveness of, different adaptation measures or levers in support of long-term resilience. 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. For example, a loss of the tax base will directly influence the ability of a community to nourish beaches and rebuild dunes. Economic considerations may also influence decisions about roadway retrofits, including construction of bridges that bypass vulnerable barrier segments (e.g., the Jug Handle Bridge in Rodanthe, NC). The dynamics that emerge from couplings between landscape evolution and evolving human decision making (e.g., McNamara and Werner, 2008a,b; McNamara et al., 2011; Williams et al., 2013), including economic aspects, will be essential to consider going forward and possible to explore in future investigations using the CASCADE modeling framework.

There are other model limitations associated with 'appropriate-complexity' models (like CASCADE) that could influence model outcomes. We direct the reader to Anarde et al. (2024a) for a complete list of model limitations related to human and natural forcings on barrier segments (or barriers of finite length). With regard to the alongshore complexities examined herein, processes that may influence potential state changes in developed barrier systems that are not explicitly modeled include 1) the post-drowning evolution of barrier segments, which may become a breach or an inlet, given sufficient flows, or reemerge to become subaerial again, and 2) the potential disintegration of barrier systems with multiple drowned segments, a phenomenon observed in modern barrier systems in the Gulf of Mexico (e.g., Moore et al., 2014; Passeri et al., 2020). Future work incorporating the effects of breaching and inlet processes, and potential recovery of subaerial extent, would enable exploration of barrier system dynamics post-drowning.

5 Conclusions

Developed barrier systems are managed for various purposes – for example, to protect roadways, properties (commercial and residential), ecological reserves, and recreation areas. Previous work has shown that in isolation, management strategies that involve construction of artificially-large dunes (in response to storms and the chronic effects of SLR), result in lower and narrow barriers over many decades as large dunes block overwash from reaching the barrier interior.

Here, we explore the complexities that emerge when dune and beach management practices vary over many kilometers. In cases of heterogeneous management practices, we find that alongshore connectivity can lead to dynamical differences in barrier evolution because of feedbacks between dunes, storms, overwash flux, and alongshore sediment transport processes. Model simulations show that the alongshore distribution of geomorphic capital, through the effects of nourishment on alongshore sediment transport gradients, can induce system-wide lags in shoreline retreat even after nourishment has ceased. Conversely, if segments of the barrier system are allowed to overwash naturally (here, along roadways or abandoned barrier segments), whereas others remain stabilized in place (here, communities that are nourishing), the overwashing barrier segments enhance curvature in the barrier system. Enhanced curvature induces larger gradients in alongshore sediment flux that acts as greater sinks for the alongshore transport system, as sediment is removed more rapidly from the beach and nearshore in overwashing segments. This, in turn, increases the frequency at which communities must nourish. Once management eventually ceases on these adjacent community barrier segments, more overwash along previously abandoned roadway segments also enhances the natural rebound of the more recently abandoned community segments.

Outcomes of potential climate adaptation measures are also influenced by alongshore couplings and long-timescale dynamics. 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 barrier interior. Barrier drowning is also a function of dune-storm stochasticity – that is, the randomness of storms overtopping a dune in its recovery state – and therefore assessing the range of potential outcomes of adaptation measures requires simulating many storm sequences and different climate scenarios. As communities explore potential levers that may allow unfavorable outcomes or system states to be avoided or delayed, our findings point to the critical importance of considering coupled human-natural interactions and the role of dune-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

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

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