Adaptation pathways for climate change resilience on barrier islands

By

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ABSTRACT

Coastal communities throughout the world will be faced with policy decisions that affect their resilience to climate change, sea level rise, and associated impacts. Adaptation pathways, a holistic approach to policy development, may be an ideal framework for municipalities to consider in low-lying, dynamic environments such as barrier islands. Adaptation pathways identify hypothetical future timelines whereby communities adopt a different policy in response to new environmental conditions. This takes into account changing conditions and resulting hazards that exceed a threshold agreed upon by the community. In this paper, we focus on barrier island communities and give an overview of adaptation pathway methodologies, highlight several common policies considered to increase resilience, review how coastal scientists have thus far contributed to such methods, and discuss specific research agendas that could aid in future implementations. Although the use of adaptation pathways is still in its early stages in many coastal communities, the success of the process is dependent on contributions from both quantitative hazard research and consistent engagement with stakeholders in an iterative co-development of prioritized policy trajectories. Scientific needs include: better understanding of future hazards due to climate change and sea level rise, better predictions of time-dependent processes such as barrier island response to human alterations to natural coastal defense systems, and improved communication between physical scientists, social scientists, managers, and stakeholders.

KEYWORDS: Adaptation, resilience, barrier islands, sea level rise, climate change.

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Coastal communities face worsening hazards due to climate change. Global temperatures have reached their highest average in more than 100,000 years due to greenhouse gas emissions, with warmer temperatures expected in the coming decades (Fox-Kemper *et al.* 2021). Global sea levels have risen an average of 3 mm/yr since 1993, with an acceleration of 0.084 mm/yr^2, suggesting higher future rates of sea level rise (SLR) due to climate change (Church and White 2011; Nerem *et al.* 2018; Dangendorf *et al.* 2019). Even in the optimistic scenario of capping global warming at 2°C, the consensus expectation from the Intergovernmental Panel on Climate Change's Sixth Assessment is that sea levels will increase 0.5 m by 2100, and almost 2 m by 2300 (Fox-Kemper *et al.* 2021). An estimated 400 million people worldwide live at elevations within 2 m of present-day mean higher high water (MHHW) tidal elevations, with many millions more within 2 m of annual flood event elevations (Kulp and Strauss 2019). In addition to increased flooding and storm damages, many populations will experience landward migration of wetlands and a squeeze of ecosystems against urban infrastructure (Kirwan and Gedan 2019), higher water tables affecting sewer and water infrastructure (Hummel *et al.* 2018; Allen *et al.* 2019), drinking water aquifers becoming saltier (Jasechko *et al.* 2020), and the erosion of beaches supporting tourism industries (Toimil *et al.* 2018).

Climate change-induced issues will be exacerbated on barrier islands, which are low-lying, shore-parallel ridges of sand separated from the mainland by shallow bays (Hayes 2005). Open-ocean shorelines are dominated by beach and dune complexes, while back-barrier shorelines are characterized by low energy environments such as wetland complexes. On its Atlantic and Gulf coasts, the United States has more than 30% of the world's 15,100 kilometers of open-ocean barrier islands (Stutz and Pilkey 2001), and these islands play an important role in mitigating hazards to back-barrier communities, economies, and cultural resources. Barrier islands are dynamic features that respond to waves, winds, tides, and changes in sea level (FitzGerald *et al.* 2008). However, they also contain desirable beach communities and generate significant tourist revenue (McNamara *et al.* 2011, Houston 2018). Barrier island populations in the United States have increased for several decades, and population densities are now more than three times higher than the average density of all coastal states (Zhang and Leatherman 2011). Coastal development and management practices have interfered with natural island dynamics, creating a coupled human-natural system that evolves in response to both external environmental forcings (ocean waves, water levels, wind, etc.) and to management policies (Oost *et al.* 2012; McNamara and Lazarus 2018). Evolution is further complicated by ocean-facing and estuarine-facing shorelines typically being managed with distinctly different policies (Jones and Pippin 2020).

The sustainability of barrier islands is uncertain. Natural barrier islands can migrate landward in response to SLR, keeping pace through episodic overwash processes during storms (known as rollover) as well as shoreward sediment fluxes through inlets (Nienhuis and Lorenzo-Trueba 2019). Forecasts suggest that warmer oceans will generate stronger hurricanes (Knutson *et al.* 2020) while also driving poleward shifts in storm tracks (Tamarin-Brodsky and

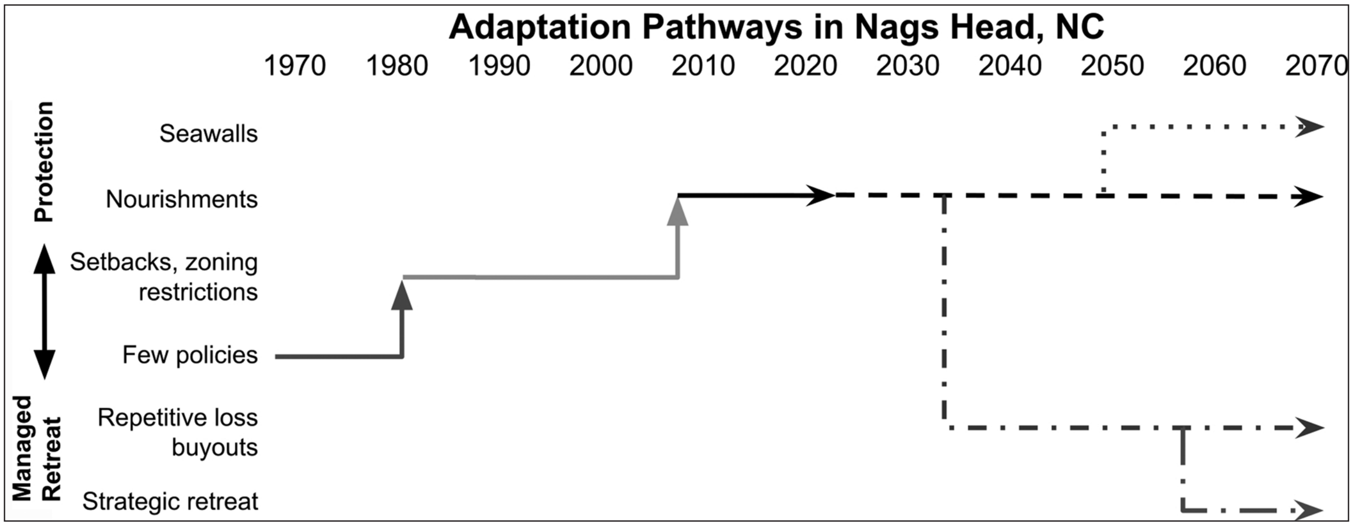

Figure 1. Historical adaptation pathways for Nags Head, NC, and hypothetical examples of pathways that could be adopted in the future. Each branch formed in the pathway is due to a potential tipping point, or exceedance of a threshold for acceptable hazards, that results in a change in policy.

Kaspi 2017), altering the wave characteristics that have maintained barrier island rollover for millennia. Background climate patterns are also expected to induce fundamental shifts in wave climates that may drive regional changes in sediment transport gradients (Morim *et al.* 2020). The relative importance of changes in wave forcing versus mean sea levels can either narrow the island width or flatten the island height (Passeri *et al.* 2020). Natural, unnourished barriers will drown completely if sea levels rise faster than rollover processes can transgress sand volumes landward and post-storm recovery processes can rebuild dune geometries through onshore sediment transport (Lorenzo-Trueba and Ashton 2014; Miselis and Lorenzo-Trueba 2017; Houser *et al.* 2015). Natural processes thus often conflict with developed island communities, which typically support strategies to protect and prevent damages to infrastructure by combating the island's natural response to climate change.

Artificial dunes and beach nourishments (Houston 2016) as well as hard structures like seawalls and bulkheads have been used to stabilize barrier islands in the short term. Simple cost-benefit analyses have suggested that beach nourishment projects can adapt to near-term sea level rise with moderate increases in sediment volume (Elko 2009). It has also been suggested that nourishments could effectively hold the present shoreline under all SLR scenarios considered by the Intergovernmental Panel on Climate Change, but the present-day understanding of how beaches will respond to SLR is limited to geometric models that assume nourishment volumes will remain local enough to their placement to raise the elevation of the equilibrium profile (Houston 2019). However, uncertainties are introduced by considering more complex beach evolution behaviors, such as the distribution of nourishment volumes, the response to increased storminess, or the long-term implications of effectively halting the natural barrier migration and recovery process. Coastal communities are faced with myriad questions, including how long soft shore protection strategies may be effective, and how much will they cost to implement and sustain indefinitely. If soft protection is no longer viable at some time in the future, when should a community invest in an alternate strategy and which of the many options are more conducive to long-term community resilience, values, and investments?

This manuscript provides an overview of an adaptation planning method that can assist communities in answering such questions. The number of studies focused on climate change adaptation has grown rapidly in recent years (e.g. Lebbe *et al.* 2021), with the goal to develop frameworks that can answer such questions by forming stronger connections between regulatory systems and scientific research (Jones and Pippin 2020). Adaptation planning generally encompasses a multi-step process of: 1) identifying a problem, 2) collecting data to quantify risks, 3) evaluating and selecting policy options, and 4) implementing and monitoring adaptation effectiveness (Bierbaum *et al.* 2013). The process is also iterative, as the effectiveness of any particular policy is neither guaranteed nor permanent due to continually changing conditions and societal needs. Large climate projection uncertainties, competing interests and values from a variety of stakeholders, unique place-specific problems, long-term time horizons, and ultimately no single correct solution cumulatively create what is known in design as a "wicked problem," which are best addressed with adaptive, participatory, and transdisciplinary approaches (Head and Xiang 2016; Yuan and Chang 2021).

Frameworks that can identify "adaptation pathways" have gained traction in the last decade as an ideal approach for informing long-term policy plans (Kwadijk *et al.* 2010; Bloemen *et al.* 2017; Lawrence *et al.* 2018). Adaptation pathways are sequences of policy/management actions that decision-makers can switch between in response to "tipping points" that occur when a policy no longer achieves desired objectives (Figure 1) (Ramm *et al.* 2018; Barnard *et al.* 2021). The year when an adaptation tipping point, or threshold, is projected to occur is known as the "use-by" year (formation of a diverging branch along the timelines in Figure 1) (Haasnoot *et al.* 2015). While present-day resilience planning is largely focused on the spatial hazard of a particular event (i.e. flood maps), adaptation pathways emphasize planning with respect to thresholds that are expected to be eclipsed at some point in time. Adaptation pathways are useful in coastal flood risk management because the drivers of impacts, such as

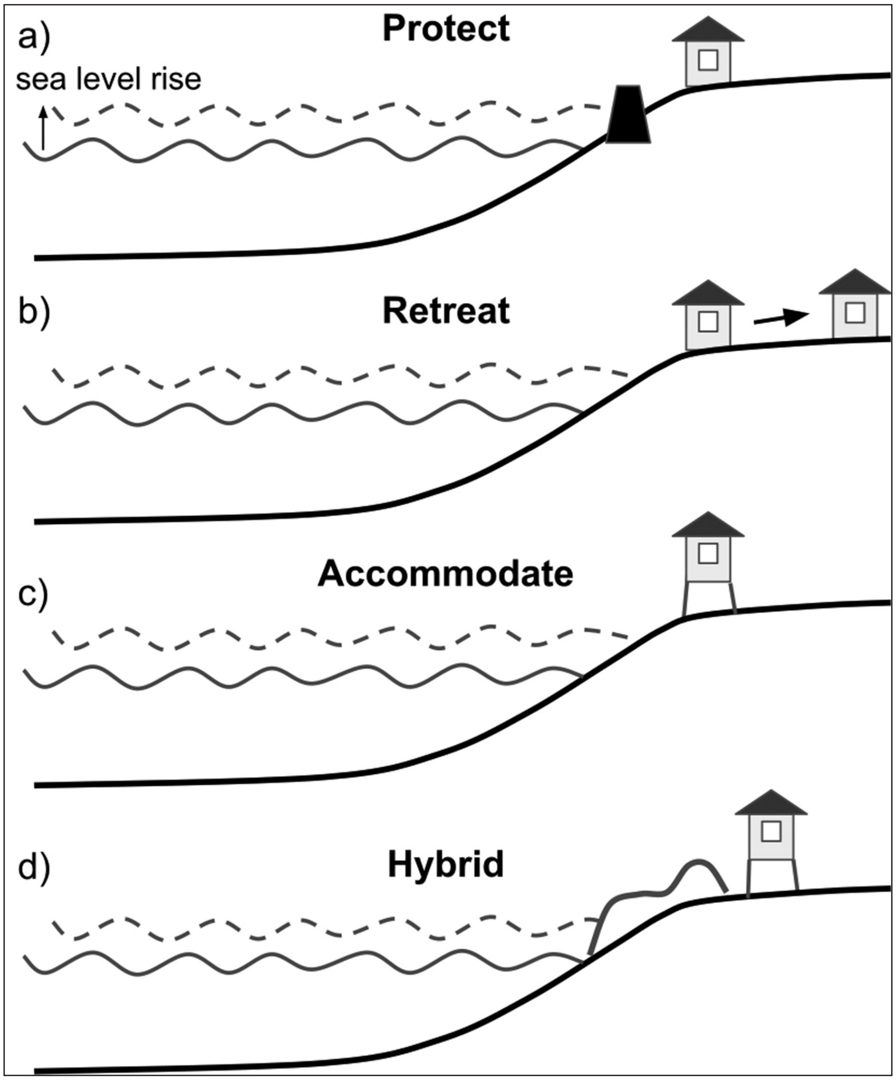

Figure 2. Common adaptations on barrier islands, including a) protection between the changing hazard (SLR) and infrastructure; b) retreating by moving infrastructure away from the changing hazard; c) accommodating for the changing hazard by increasing the present infrastructure's resilience; and d) hybrid policies like a nourishment combined with elevated buildings.

SLR, are characterized by slow-moving trends, suggesting the point in time when a use-by threshold will be exceeded can be predicted with more certainty than in rapidly changing systems (Bloemen *et al.* 2017). While generic pathways have been identified for broad coastal archetypes, localized pathways specific to a coastal setting and its particular management goals will necessitate that many coastal communities commit to identifying their own tipping points (Haasnoot *et al.* 2019).

In this paper, we review the general application of adaptation pathways as a 21st-century resilience policy mechanism for barrier island communities in the United States. We discuss the broad policy options typically considered in adaptation pathway frameworks as well as the range of physical modeling techniques used to support decisions. Specific barrier island examples are provided along with key limitations and future developments that may improve the success rate of adaptation pathways as a mechanism for addressing the impacts of coastal hazards.

COMMON POLICY OPTIONS ON BARRIER ISLANDS

An ideal attribute of adaptation pathway frameworks is the flexibility to consider a wide range of policies and their eventual implications. This flexibility allows participants to understand the range of potential outcomes and consequences associated with each decision (Walker *et al.* 2013). For barrier islands, common policies include either protection by any means necessary or managed retreat from damaged buildings or threatened properties, as well as middle-of-the-road policies that provide some form of accommodation (Figure 2).

Protection

The most common practice today on United States barrier islands is to protect property and maintain current island footprints. However, "hold the line" strategies can still follow a wide variety of policies as alternative pathways (Figure 1). Strategies include hard engineering options, such as the large, open-ocean seawall along the barrier island of Galveston, Texas, as well as smaller property-specific bulkheads that can be found on back-barrier sound-side properties throughout the United States' Atlantic and Gulf coasts. Alternatively, soft engineering options, notably beach nourishment, have been adopted by many barrier island communities as the preferred form of protection in the United States (Armstrong *et al.* 2016, Elko *et al.* 2021).

Beach nourishment is recognized as an effective open-ocean shoreline stabilization strategy (Luettich *et al.* 2014, Readshaw *et al.* 2017), both as a buffer between infrastructure and storm wave attack and as a source of sand that encourages natural dune building processes (Kaczkowski *et al.* 2018). It is difficult to quantify the relative effects of wider beaches compared to larger dunes following beach nourishment, but the combined effect has demonstrated the ability to mitigate energetic storm and hurricane risks. Hurricanes Dennis and Floyd (1999) affected the North Carolina (NC) barrier islands, caused no damages to buildings protected by three U.S. Army Corps of Engineers (USACE) projects, but damaged or destroyed more than 900 buildings along adjacent unnourished shorelines (Rogers 2007). The success of these nourishment projects has contributed to an exponential growth of sand volumes placed on United States beaches (Landry 2011; Elko *et al.* 2021). In NC, more than $465 million has been spent on about 38 million cubic meters of sand for shore protection and emergency nourishments since 2010, not including nourishments resulting from navigation-related dredging (APTIM 2021). Figure 3a is an aerial photo of a renourishment project in 2019 in the barrier island community of Nags Head, NC. The original nourishment in 2011 performed well at retaining sand volumes for the initial five years but lost considerable volumes during the extreme waves and water levels of

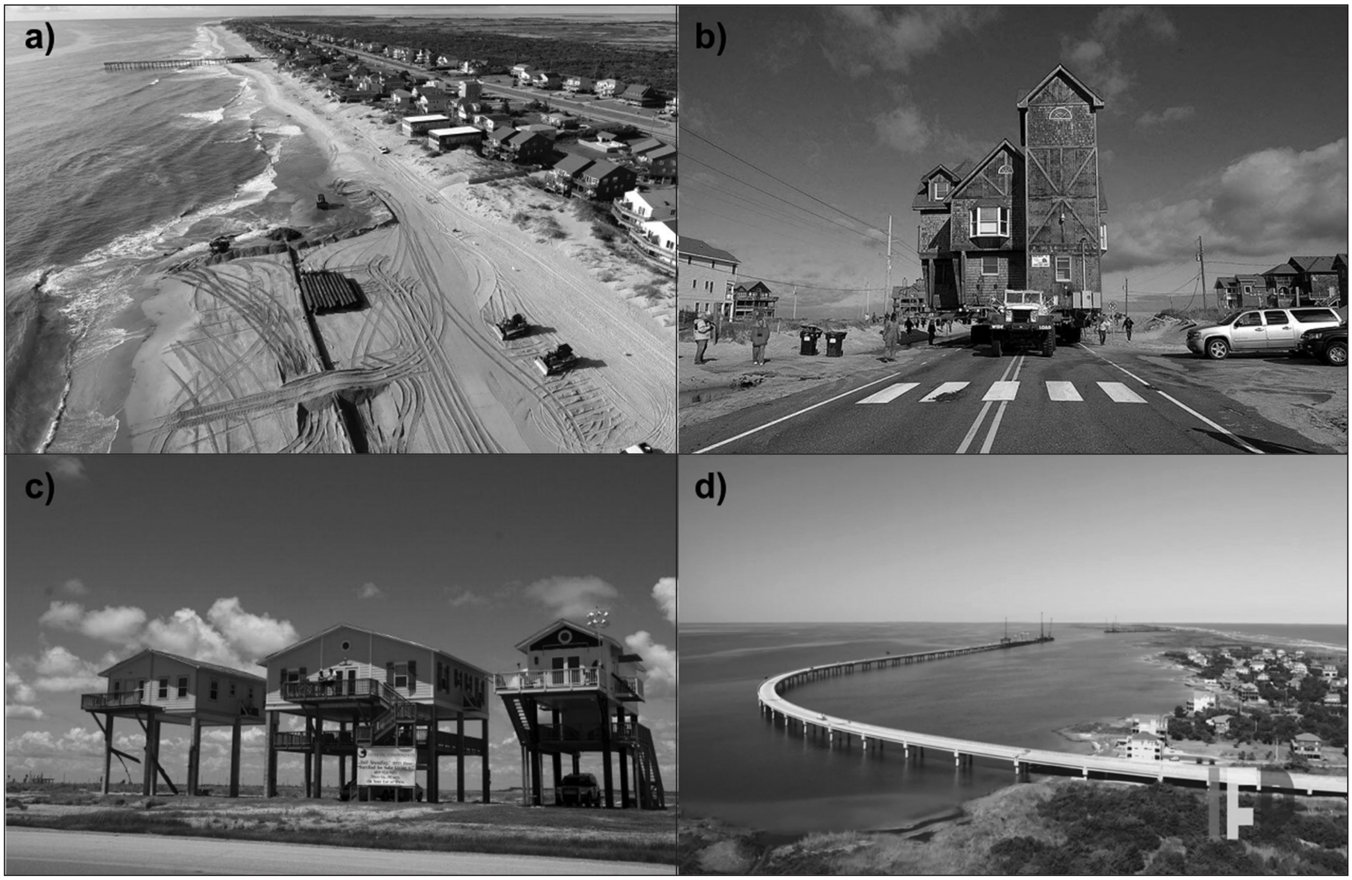

Figure 3. Examples of a) renourishment in Nags Head, NC; b) managed retreat in the form of a house relocation in Rodanthe, NC; c) elevated oceanfront homes that survived Hurricane Ike in Gilchrist, TX; and d) construction of a bridge in the Outer Banks, NC, that is elevated and located in the back-barrier sound to avoid highway erosion. Photos courtesy of Town of Nags Head, NC; Dan Bowers, The Island Free Press; Patsy Lynch, FEMA, and The Island Free Press, respectively.

Hurricane Matthew (2016). In the years following, the beach became narrow and dune scarping occurred such that flood protection was reduced beneath the town's acceptable levels (personal correspondence with town engineer). Another renourishment is planned for 2022 to account for the sand volume lost during Hurricane Dorian (2019). Typical nourishment frequencies in the United States are every 10 years, with variability dependent on the local background erosion rate (Cuttler *et al.* 2019) and hurricane activity (Elko *et al.* 2021).

Barrier island communities that opt to hold shorelines in place are often supported by federal government subsidies, which have kept the option economical relative to the resulting tourist revenue (e.g. Houston 2018). Such support is typically justified by the value of the land being protected; a feedback can result as valuable waterfront real estate is deemed worthy of protection via nourishment, which leads to further investment in those properties, further growth in real estate value, and thus further justification for more protection (Armstrong *et al.* 2016). In addition to federal aid, nourishments are preferred by some communities that have access to affordable sand resources, or have navigation channels that must be dredged for shipping (Neal *et al.* 2019). However, the long-term viability of beach nourishment is uncertain. Higher water levels will create more accommodation space for nourishment sediments to be pulled offshore, potentially increasing the frequency and total volume of sediment needed per nourishment (Passeri *et al.* 2021). Sediment sourcing may also limit long-term sustainability as local sources are depleted by the present and future demand (Ousley *et al.* 2014). The protection strategy is also typically limited to the open-ocean shoreline, which limits open ocean storm impacts and can reduce the likelihood of island breaching (both ocean-front and bay-side breaching processes, (e.g. Over *et al.* 2021), but does not protect the back-barrier shorelines from future SLR and the future impacts of nuisance flooding. A recent USACE report specific to New Jersey suggested that back-barrier storm surge barriers would cost more than $16 billion (USACE 2021), highlighting that the cost of protecting all sides of barrier islands can grow to unfeasible levels.

Managed retreat

Managed retreat is based on a philosophy of avoiding or moving out of harm's way, and ranges in scale from the relocation of a single building to whole communities (Neal *et al.* 2019). Managed retreat minimizes costs from recurring hazards, but it can take several forms including proactive avoidance enacted prior to events, as well as more passive unplanned abandonment after an event. Implementation has numerous challenges, mostly political and socioeconomic, such as real estate markets, subsidized flood insurance programs, local governments that want to grow to expand the tax base, and turnover of appointed political figures (Gibbs 2016). Community resistance can result from both cultural "sense of place" and investments in property. Nevertheless, a variety of management tools can be considered within such a

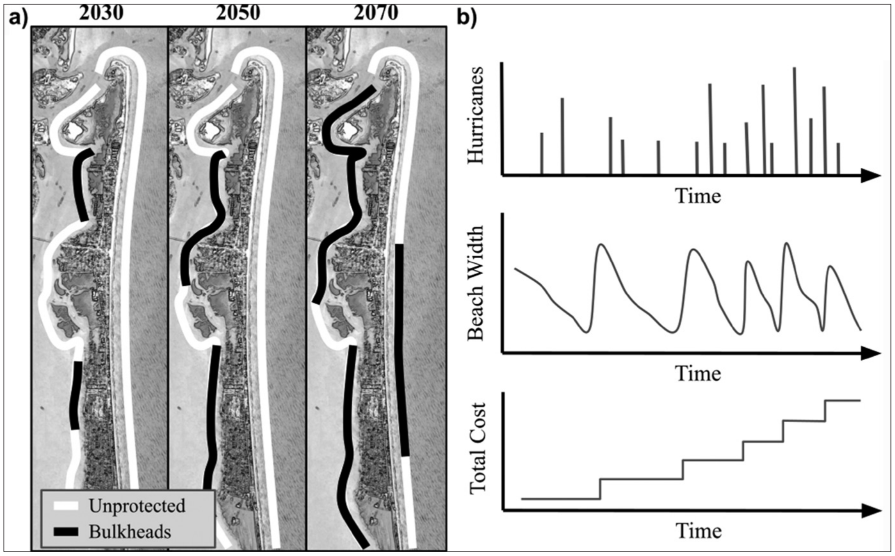

Figure 4. Hypothetical examples of how adaptation pathway methods can be communicated with stakeholders: a) spatial changes to the community resulting from the construction of protective walls after flooding exceeding a threshold limit; and b) temporal tracking of amenities (beach width) and costs of repeated beach nourishment following hurricanes.

policy, including development zoning restrictions, setback limitations, not allowing shore protection structures, public land buyouts, or economic disincentives like limited insurance and higher taxes.

The earliest example of complete relocation away from a United States barrier island is Diamond City, NC, when a small community moved to a more-protected island in the sound in 1899 following an intense hurricane (Neal *et al.* 2019). Relocation of entire communities is less common today in part because communities are larger and more established with respect to public and private infrastructure, but also because both hard and soft engineering options are feasible at local and regional scales. Instead, the most common manifestation of managed retreat is in response to policies enforced on a property-by-property basis. Some towns and counties have enacted post-storm regulations that prevent rebuilding a damaged home in the same place, but these are stricter policies than required by federal or state legislature. The Town of Nags Head, NC, intentionally required ocean-fronting structures to be constructed of "movable material" and created and/or consolidated building lots in the 1970s and 1980s to create long, skinny plots perpendicular to the shoreline such that homes could be relocated backwards on the same property (Nags Head 1980). A common practice throughout the Outer Banks is to relocate structures in danger of collapsing into the ocean (Figure 3b). Perhaps the most publicized modern-day barrier island "retreat" example is the moving of Cape Hatteras Lighthouse about 1 km back from the shoreline in 1999 in Buxton, NC. The proposal to move the lighthouse faced strong headwinds from the local community but has proven to be a worthwhile return on investment for the tourist industry and has served to educate the public about potential benefits of managed retreat.

Accommodation

Accommodation is between the binary ideas of protection and retreat. The idea is to allow residents to remain in place by increasing the resilience of a property. The most common form of accommodation is to implement regulations like updated building codes that require retrofitting structures. Alterations to existing structures can include elevating the building with pilings, reinforcing with stronger materials, or designing infrastructure to be submersible (i.e. storm drains that can be closed). Figure 3c shows three houses in the barrier island community of Gilchrist, TX (fronting Galveston Bay), that survived Hurricane Ike in 2008. The houses were elevated higher than their neighbors, allowing for water velocities associated with surges and waves to pass under the structures. The effect of such building code policies often has a lag associated with implementation, as only new or renovated structures must abide by the present-day code. Such policies are also more expensive to construct, which can drive a transition to more affluent property owners and higher rental prices to offset construction costs (Hamideh *et al.* 2018).

Hybrid policies

Policies rarely fit within one adaptation approach. Forward-thinking infrastructure designs aim to increase resilience by adopting elements from multiple policies. An early example is the mixing of both a continuous seawall and nourishment to protect Galveston, TX, in the early 1900s. More recent innovative approaches include the NC Department of Transportation constructing a $145 million, 2.4-mile-long bridge in 2021 that bypasses an erosion-prone portion of a state highway that provides the only road access for supplies and emergency personnel to multiple barrier island communities along the southern portion of the Outer Banks. The elevated roadway runs parallel to the barrier island, about 2,000 ft into the back-barrier sound (Figure 3d). This infrastructure adaptation is an example of both accommodation (elevating the roadway and allowing natural barrier island washover processes to occur) as well as managed retreat (relocating the roadway to a setback location where calmer environmental forcing will interact with the structure). However, at more than $60 million per mile of highway, this option would be very expensive to employ on larger scales.

Many barrier island communities have blended protection and accommodation into single policies that attempt to increase resilience by both stabilizing the beach with artificial dunes and requiring homes to be elevated. The specific policies can vary on a property-by-property basis. Some states consider exceptions for those properties that may be grandfathered into older policies or have stricter policies for public infrastructure compared to private residences (Shelburne 2020). This patchwork approach, where neighboring properties abide by different policies, can lead to unforeseen feedbacks and weaknesses within the community. A common example on barrier islands is the scenario in which an older home is not required to elevate, becomes a large floating debris hazard during a storm surge event, and then damages or destroys neighboring elevated homes that otherwise would have been resilient to the event.

IDENTIFYING TIPPING POINTS

The effectiveness of the common policy options outlined can be examined by combining them into sequences, or adaptation pathways, adopted over time in response to environmental changes that alter the community's risk exposure. Identifying the tipping points that trigger a change in policy requires quantifying the physical impact of hazards that could occur without policy implementation, as well as the cost of that implementation. Hazard impact is typically predicted through exploratory modeling with varying degrees of fidelity ranging from empirical to physics-based simulators. Many hypothetical future scenarios are evaluated to assess the consequences of each policy subjected to potential future environmental conditions.

A common approach is scenario-based simulations, whereby cases of environmental conditions (winds, waves, water levels) are simulated on a hypothetical landscape configuration representative of a particular policy. The relative performance of each policy can be assessed by comparing cases with the same environmental forcing simulated on different configurations (i.e., flooding on a domain with a nourishment versus a similar domain with seawall in place of the nourishment). Tipping points for a particular policy can then be assessed by subjecting the same landscape configuration to varying environmental conditions. This process can grow the number of cases beyond the available computational resources, necessitating that only a subset of particular scenarios be selected, or that a simplified empirical model be employed. As an example, Smallegan *et al.* (2017) developed adaptation pathways by modeling the response of a nourished barrier island to a single storm acting on three different sea levels. Several nourishment and dune configurations were considered, but a total of only 30 cases were simulated due to the computational requirements of the process-based morphodynamic model. Although this approach can be useful as an initial screening to identify a more focused set of pathways to explore, it highlights the difficulty of performing such an analysis on a community-by-community scale along the entire coast.

Recent efforts have considered time-explicit frameworks as a method for constraining not just the environmental conditions that exceed a tipping point, but also when those conditions are more likely to occur in the future due to SLR. One approach is to model storm conditions with high fidelity, and subsequently determine when each storm occurs with a probabilistic function constrained on historical observations (Males *et al.* 2007). Time is then made continuous by assuming all non-stormy periods can be modeled by an average background recovery rate (Passeri *et al.* 2021). A more robust approach is to generate Monte Carlo simulations of hourly or daily coastal conditions and use simplified geomorphic models (Mills *et al.* 2018). These methods capture more time scales of variability than simply the extreme storms and generate time-dependent uncertainties (Mills *et al.* 2021).

Both scenario-based and time-explicit approaches can have useful results for communicating impacts to stakeholders and policy makers. The goals are to communicate how their community will look if such an adaptation pathway is employed, and to allow the public to identify certain futures they would prefer to avoid. Spatially explicit impact maps can convey where tipping points will occur. Figure 4a provides a hypothetical example of how scenario-based impact results could be shared with stakeholders considering a policy that builds hard-engineering seawalls after flooding events that cause a certain threshold of damage. Alternatively, time-explicit results are useful for considering policies that require constant maintenance, such as nourishments. Figure 4b shows a hypothetical scenario for a town considering a future policy of nourishing whenever storm erosion has reduced the beach width below some critical threshold. Managers can then use the predictions to have a better understanding of when the cost of that policy could become prohibitive, and the potential frequency that they will need to nourish in order to enjoy the amenity of a wide beach.

A number of studies have developed simplified theoretical models that account for time-varying coastal conditions (e.g. Lazarus *et al.* 2011), however their focus has largely been on identifying general trends and internal dynamics as opposed to any site-specific adaptation measures. To the authors' knowledge, a fully temporally- and spatially-explicit framework accounting for future hypothetical environmental conditions at high resolution (hourly to daily) has not been applied to a barrier island community. Nevertheless, academic case studies with idealized tipping points have demonstrated the potential of time-explicit models (e.g. Karanci *et al.* 2018), and efforts to initiate the development of adaptation pathways by gathering local information and engaging the public have become more common in the last decade. Vulnerabilities and local stakeholder priorities have been assessed for coastal communities on Sullivan's Island, SC (Tuler *et al.* 2010), and Orange Beach, AL (Webler *et al.* 2012), while the process has reached more formal policy recommendations and SLR adaptation plans on Dauphin Island, AL (Janasie 2015), and Tybee Island, GA (Evans *et al.* 2013). Several of these community engagements were conducted through a program known as "Vulnerability, Consequences, and Adaptation Planning Scenarios" (VCAPS), which has successfully brought community members together to identify issues requiring further exploration or data needs (Tuler *et al.* 2020), highlighting that valuable progress can be made by considering more qualitative descriptors when co-developing adaptation plans with stakeholders.

LIMITATIONS AND FUTURE NEEDS

The research and active use of adaptation pathways are still in their infancy and likely to evolve as case-study applications reach mature insights and as vulnerable communities adapt the methods with different needs or desired outcomes. Future research needs can be grouped into three general themes: developing methods for generating hypothetical environment forcings that account for uncertain future projections, improving resilience modeling frameworks to account for greater fidelity, and incorporating methods for co-developing desired policy adoptions that are representative of stakeholder populations.

■ *What future environmental conditions to consider?*

To determine the best adaptation pathway, the community must first determine what future environmental conditions to consider. The environmental conditions depend on fundamental physical scientists narrowing the uncertainties in future climate projections, such as tighter ranges of possible SLR scenarios and better constraints on future hurricane characteristics. However, such uncertainties will always be present to varying degrees, suggesting frameworks will need to account for uncertainties through dedicated methods (Walker *et al.* 2013). Ideally, the full range of possible futures resulting from both uncertainty and natural variability will be used to inform adaptation. This full range will likely require a greater number of hypothetical scenarios and dedicated techniques for choosing such scenarios.

One deterministic approach is to downscale local hazards by using the outputs from global circulation models (GCMs) simulated at varying global greenhouse emission scenarios, known as Representative Concentration Pathways (RCPs) (Vousdoukas *et al.* 2016). This downscaling has a high computational demand, and its limited number of realizations can lead to large uncertainties. However, GCM fidelity has improved rapidly, and the development of frameworks that can use, or be informed by, GCM outputs will be a research need in the coming decades.

Alternatively, probabilistic approaches such as Monte Carlo simulations can provide many realizations of future conditions, including varying storm climate frequencies and intensities superimposed on a wide range of SLR scenarios. Recent developments allow for hypothetical futures containing time-explicit conditions that enable chronological behavior to be simulated, including morphodynamics and internal feedbacks (Anderson *et al.* 2019). The ability to produce many realizations allows for more confidence with respect to extremes and for more robust uncertainty statistics. Many communities design for return period extreme events such as the 1-in-100 year water level, and thus frameworks that can quantify how those return periods will change into the future will be in high demand. Such improvements with respect to likely future environmental conditions will improve adaptation pathway development by focusing already limited time and energy resources on preparing for the most likely future hazards.

■ *Which hazard impact models should be used?*

The models used to determine resilience contain several limitations. Process-based, high-fidelity models are the scientific community's best approximation of real-world physics, but these models contain errors that affect any derived resilience product, such as flooding extents or predicted building damages. Errors with respect to morphodynamics, such as dune erosion, barrier breaching, and hot-spot erosion of nourishments, can be particularly large unless models are tuned to specific scenarios (Gharagozlou *et al.* 2020), but can have significant effects on the ultimate hazard experienced on barrier islands due to their predominantly unconsolidated sediments. The most accurate simulations require high spatial and temporal resolution while simulating storms of short duration, which results in large computational needs and limits the ability to consider many hypothetical scenarios.

An additional challenge is that fully dynamic models are too expensive to be applied for decadal simulations to resolve chronic issues like persistent erosion and nuisance flooding that do not result from extreme events. Emulation, and the ever-growing capabilities of machine learning algorithms, have the potential to address some of these knowledge gaps (Goldstein *et al.* 2019). There is promise for machine learning algorithms to improve fidelity in large-scale modeling domains by approximating unresolved small-scale physics, as well as the potential for surrogate models to enable a reasonable hazard impact to be predicted from a library of pre-run simulations (Parker *et al.* 2019; Anderson *et al.* 2021). However, surrogate modeling efforts are limited with respect to morphodynamic behavior, and novel approaches must be developed before they can be useful in adaptation efforts that are considering erodible surfaces. Other improvements that may aid this line of research include faster processors and more efficient numerical modeling algorithms.

Ultimately, adaptation pathways are predicated on the ability to make predictions of future hazards and future feedbacks between societal actions and natural forces. Improvements in our modeling capabilities to make accurate predictions will ensure that conversations with coastal communities are engaging and productive, and accurately communicate future risks.

■ *How is an agreement reached for implementation?*

Adaptation pathways can diverge to produce different future conditions, and the perceived success is largely dependent on the values and priorities of the community. A fundamental element of the process of choosing an adaptation pathway is input from the local community regarding the future they would prefer (Lin *et al.* 2017). This can be contentious, because not all future desires can be accommodated in any adaptation pathway. Polling the residents is insufficient because the average stakeholder must be educated to make an informed decision. Engagement with the public can be a time-consuming process occurring over multiple iterative sessions and involving discussions between scientists, policy makers, and community members, a process that is broadly termed "co-development" (Lipiec *et al.* 2018). Greater likelihoods of equitable outcomes are associated with attracting a diverse representation of the broader community to such sessions. However, the shared values obtained during these sessions are often biased toward people with strong opinions and free time to participate, and rhetoric that has politicized climate change further complicates the process of engaging the community (Bulla *et al.* 2017; Covi *et al.* 2021). Barriers to implementation have culminated in few projects reaching the implementation stage, especially in scenarios with multiple levels of governance (Kettle *et al.* 2014).

There are several methods intended to aid in making difficult and contentious decisions. Structured decision making has been used to identify pathways that best preserve cultural resources on barrier islands (Fatoric and Seekamp 2017), as well as assisted in making complicated decisions concerning the artificial closure of a barrier island breach affecting ecosystems, navigation, and flooding resilience (Dalyander *et al.* 2016). Cost-benefit analyses can also inform choices by identifying pathways with the greatest benefits for the local tourist economy, the environment, and the real estate market (André *et al.* 2016). However, even if a community agrees on a particular adaptation pathway, the debate for how to fund that strategy can produce conflict. Take for instance, the use of tax dollars to fund a beach nourishment that disproportionately benefits oceanfront homes relative to more inland homes, both in the form of protection and home value. How should the community decide on "fair," spatially dependent, tax responsibility? A recent review of coastal adaptation projects found that local governances require assistance in the stakeholder communication process, as a limited number were able to successfully engage in pathway discussions (Lin *et al.* 2017). Unfortunately, there are relatively few social science professionals equipped with the knowledge and tools to navigate a community through the decisions associated with an adaptation pathway framework. Further development of equitable techniques for science communication and group decision making would greatly aid in the co-development phase of adaptation pathways, while training scientists and managers alike in the skills to facilitate localized adaptation pathways will increase likelihoods of successful implementation.

ADAPTATION PATHWAYS IN ACTION: NAGS HEAD, NC

The Town of Nags Head, NC, is a barrier island community in the northern Outer Banks, and is recognized as a proactive community engaged in climate risk mitigation (Neal *et al.* 2019). It has more than 18 km of linear beach fronting the Atlantic Ocean, and more than 73 km of low-lying back-barrier shoreline facing the Albemarle and Pamlico Sounds to the west (Kaczkowski *et al.* 2018). The town is one of the oldest beach vacation communities in the United States, and it has a year-round population of less than 3,000 but a peak summer population of approximately 40,000. To preserve their family beach atmosphere, Nags Head implemented managed retreat elements into its "Repetitive Loss Plan" and "Floodplain Management Plans" as early as 1995 (Bush *et al.* 1996). The town continually commits to incorporating scientific advice within each plan, including introducing Geographic Information System (GIS) technology in the 1990s to assess the impact of development patterns on flooding (Esnard *et al.* 2001). A tipping point was reached by the late 2000s, when the town began exploring avenues to cost-effectively incorporate beach nourishment by obtaining assistance from federal and state government sources (Kaczkowski *et al.* 2018). The success of their large-scale nourishment in 2011 is cited by numerous barrier island communities as an adaptation example to emulate in their five-year plans. However, a renourishment was required in 2019, and another is planned for 2022, highlighting that this adaptation is a temporary fix.

Nags Head has recognized that there is a need for increasing resilience to future hazards. In 2015, the town began a multi-year effort in partnership with North Carolina Sea Grant to synthesize their community's values and co-develop potential future policies through their own VCAPS effort (Tuler *et al.* 2020). Targeted interviews and multiple group meetings documented stakeholder concerns about potential hazards. Facilitators provided scientific information to inform the discussions. The conversations were summarized in visual diagrams to prioritize decisions and hazards by using a weighted voting system. Town managers recognized that more scientific information was necessary, and a joint effort was initiated with the University of North Carolina at Chapel Hill and the University of Georgia to better understand flooding impacts and identify specific vulnerable buildings.

Although the community has only recently engaged in the holistic process of considering future adaptation pathways, its history is a demonstration of how policies change in response to the changing hazards and the town's priorities. Forward projecting and prioritizing a specific future adaptation pathway is still an ongoing effort in Nags Head, highlighting that the processes of identifying problems, obtaining data, and gathering community input are resource intensive and that the development of future pathways can take multiple years. Figure 1 shows the Nags Head historical adaptation pathway and a hypothetical example of several strategies that could be considered, depending on the outcomes from ongoing hazard assessments. Although similar in concept, the complete list of options being considered is more specific, including targeted efforts for open-ocean beach management, back-barrier shorelines, and sewer infrastructure. The difficult work ahead will be constraining when the tipping points will require a divergence from the present-day beach nourishment policy.

CONCLUSION

The field of climate adaptation has developed in response to a growing number of natural disasters and in recognition that adaptive strategies are essential for long-term planning in the face of climate change (Parkinson and Ogurcak 2018). These disasters are a consequence of a changing climate altering local environments and populations growing such that communities are now experiencing hazards they were not designed to handle. This is especially true on low-elevation barrier islands, where SLR will cause elevated water levels and therefore increase the frequency of damaging storm surge flooding unless communities actively adapt and become more resilient. Adaptation pathways have gained ground as a generalizable method for envisioning plans considering both where and when to enact new resilience strategies as water levels continue to rise. While the use in barrier island communities is still in its infancy and several case studies have not yet reached successful completion, the framework is ideal for dynamic systems where it is anticipated that policies will need to change as the environment changes.

The iterative and collaborative process of adaptation planning has been implemented in land conservation and habitat preservation more frequently than in hazard mitigation (Kettle *et al.* 2014). Challenges include difficult decisions, hazards not yet experienced (and thus hard to conceive), and wide uncertainty in climate projections and associated impacts. The coastal science community has developed frameworks that can forecast both spatial and temporal hazards contingent on hypothetical management policies, but improvements in fidelity, uncertainty quantification, and communication will be critical to adaptation success in the 21st century.

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Editorial

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Jacksonville or protection of inland areas from flooding. As an added support for beach nourishment, Dr. Houston has also provided the "New 2021 Sea level rise projections by the Intergovernmental Panel on Climate Change." This Coastal Forum provides a summary of the most recent IPCC report and reflections on how these latest projections might alter decisions for beach nourishment.

Many *S&B* readers or folks who attend ASBPA conferences know Scott Douglass, designer of beaches and wetlands, author of guidance manuals, and tie-er of flies. Maro Pontiki has prepared an interesting interview of Scott as one of the O'Brien winners. Scott taught coastal engineering for years, learning along the way from his peers and his students. When he is not fly-fishing in the Rocky Mountains, he is an advocate for training and educating our next generation of coastal professionals.

Two final papers in this issue address coastal management issues. One is "Strategic approaches to sediment management for restoration of a deltaic plain" by Syed M. Khalil, and others. The Mississippi delta plain in coastal Louisiana is experiencing massive erosion rates and along this part of the coast, sediment means survival. Over 800 square miles of land need to be built or maintained for ecosystem restoration. Such massive restoration needs sediment. Immediate sediment needs are about 148-160 million cubic yards, but near- and long-term needs could exceed 60 billion to more than 100 billion cubic yards. To help this effort, the State of Louisiana has surveyed available sediment sources from both active placement and passive water diversions and developed a database to archive these supplies.

The other paper is "Adaptation pathways for climate change resilience on barrier islands" by Dylan Anderson, *et al.* Communities on low-lying barrier islands are some of the first areas experiencing rising sea level and the sustainability of these areas is uncertain. Adaptation pathways will allow community members and decision-makers to examine various adaptation options, including protection or managed retreat. Accommodation and hybrid policies and tipping points at which policy approaches may need to change. The authors acknowledge uncertainties in the effectiveness of various coastal management approaches and that the use of adaptation pathways is in its infancy. Challenges to the use of adaptation pathways include difficult decisions, hazards not yet experienced (and thus hard to conceive), and wide uncertainty in climate projections and associated impacts.

Rounding out the issue are the winners of the photo contest and their incredible observations of the coast. Like rogue waves, we know well that the coast is an amazing place. These photos help record different coastal areas, and help us remember why we work to protect the coast.