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Key Points:

- With increasing shoreline erosion and landward retreat, Fire Island was predicted to become flatter, narrower, and more overwash-prone
- Beaches are expected to be least impacted and to replace other landcover types as they migrate with the shoreline
- Habitats used by piping plovers are expected to persist as long as development and stabilization structures do not limit beach migration

Supporting Information:

Supporting Information may be found in the online version of this article.

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Predicted Sea-Level Rise-Driven Biogeomorphological Changes on Fire Island, New York: Implications for People and Plovers

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Abstract Forecasting biogeomorphological conditions for barrier islands is critical for informing sea-level rise (SLR) planning, including management of coastal development and ecosystems. We combined five probabilistic models to predict SLR-driven changes and their implications on Fire Island, New York, by 2050. We predicted barrier island biogeomorphological conditions, dynamic landcover response, piping plover (*Charadrius melodus*) habitat availability, and probability of storm overwash under three scenarios of shoreline change (SLC) and compared results to observed 2014/2015 conditions. Scenarios assumed increasing rates of mean SLC from 0 to 4.71 m erosion per year. We observed uncertainty in several morphological predictions (e.g., beach width, dune height), suggesting decreasing confidence that Fire Island will evolve in response to SLR as it has in the past. Where most likely conditions could be determined, models predicted that Fire Island would become flatter, narrower, and more overwash-prone with increasing rates of SLC. Beach ecosystems were predicted to respond dynamically to SLR and migrate with the shoreline, while marshes lost the most area of any landcover type compared to 2014/2015 conditions. Such morphological changes may lead to increased flooding or breaching with coastal storms. However—although modest declines in piping plover habitat were observed with SLC—the dynamic response of beaches, flatter topography, and increased likelihood of overwash suggest storms could promote suitable conditions for nesting piping plovers above what our geomorphology models predict. Therefore, Fire Island may offer a conservation opportunity for coastal species that rely on early successional beach environments if natural overwash processes are encouraged.

Plain Language Summary Predicting a barrier island's future characteristics is important for planning, particularly given that these areas contain habitats used by threatened and endangered species and are popular sites for housing and recreation. In this study, we combined five models to predict barrier island characteristics like elevation, beach width, and dune height under three rates of shoreline erosion at Fire Island, New York. Models were also used to predict how likely parts of the island were to be permanently flooded by sea-level rise or to experience overwash with storms, where waves move sand deeper into the island. We found that Fire Island would likely become narrower and flatter while experiencing more overwash with storms as rates of shoreline erosion increase. These changes may lead to more flooding in housing communities and businesses on the island. However, models also predicted that beach habitats used by shorebirds like the piping plover would not flood permanently. Instead, they would move as the shoreline changes position as long as human structures like buildings or seawalls do not block sand movement. This migration of beaches and sand is important, as it also allows a barrier island to evolve and survive with rising sea levels.

1. Introduction

Barrier islands are highly dynamic landforms shaped by wind, waves, water levels, currents, and vegetation (Davis jr, 1994; Leatherman, 1983). As a result of these forces, barrier islands experience nearly constant alterations to the shoreline and subaerial footprint (Dolan et al., 1988; Morton & Sallenger, 2003; Philips, 2017), with evolution constrained by sediment availability and human modifications to the landscape (Armstrong & Lazarus, 2019; Ciarletta et al., 2021; Hapke et al., 2010; Lorenzo-Trueba & Ashton, 2014). Highly complex relations among natural disturbance regimes, substrates, and biological communities present on a barrier island can lead to equilibrium conditions in geomorphology and ecological community composition that can remain

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stable over centennial or millennial time scales (Ahnert, 1994; Cooper et al., 2007; Holling, 1973; Stallins, 2006; Zinnert et al., 2017). This interplay of factors can result in, for example, a high-elevation barrier island dominated by late-successional plant communities or a low-elevation, overwash-prone barrier island dominated by early successional communities (Vincent & Moore, 2015; Zinnert et al., 2017). Novel conditions or disturbances can cause a shift in a prevailing geomorphological and ecological (hereafter, “biogeomorphological”) state, whereby self-reinforcing mechanisms make a return to the previous state unlikely (Scheffer et al., 2012; Vincent & Moore, 2015).

Understanding relations among dynamic drivers, biogeomorphological responses, prevailing landscape conditions, and potential state shifts are important for managing barrier islands, with implications for both human use and species management. Although biogeomorphological states are expected to shift regularly in these dynamic environments, increased rates of sea-level rise (SLR) combined with storms are predicted to cause faster and more abrupt changes to barrier island characteristics (Brinson et al., 1995; Scheffer et al., 2012; Schneider, 2004) with substantial, well-documented socioeconomic and ecological consequences (Arkema et al., 2013; Chown & Duffy, 2017; Hallegate et al., 2013; Hauer et al., 2016; Hinkel et al., 2014; Leatherman, 2001; Neumann et al., 2015; Scheffer et al., 2001; Von Holle et al., 2019). Most likely estimates of SLR by 2100 are 1 m higher than that observed in the 1991–2009 epoch, with worst case scenarios predicting a 2.5 m increase by that time (Sweet et al., 2017). High rates of SLR are of particular concern because they may drive inundation state shifts, where previously subaerial ecosystems (e.g., sandy beaches, tidal marshes) become permanently flooded marine ecosystems. While some ecosystems and landcover types may respond dynamically to SLR (Lentz et al., 2016), an entire barrier island and its component ecosystems are at risk of drowning if a low sediment budget and other factors inhibiting landward migration or “rollover” prevent the system from keeping pace with SLR (Lorenzo-Trueba & Ashton, 2014; Nicholls & Cazenave, 2010; Passeri et al., 2020; Sallenger, 2000; Stockdon et al., 2007). Anticipating changes in barrier island biogeomorphological characteristics, therefore, requires consideration of the natural complexity, variability, and dynamism inherent to these systems, alongside considerable uncertainties associated with the forcing factors that will shape them.

Planning for SLR impacts on coastal landscapes—including anticipating where and when important biogeomorphological state shifts may occur—has been difficult because of a paucity of approaches capable of integrating complex, nonlinear biogeomorphological relations (Stallins, 2006; Zinnert et al., 2017). For example, widely available inundation models that primarily consider elevation (e.g., Marcy et al., 2011; Strauss et al., 2012) have offered an initial understanding of where low-elevation landscapes are most at risk of being inundated with SLR. However, some ecosystems and geomorphic settings are able to move and persist with SLR in what is termed a ‘dynamic response’ (Lentz et al., 2016). Models are likely to overestimate flooding and inundation predictions when they do not consider the potential for coastal landforms to respond more dynamically to SLR, such as beaches (Lentz et al., 2016).

Our objectives in this work were (a) to investigate a barrier island's propensity for dynamic change and to forecast possible biogeomorphological conditions in 2050 under multiple SLR-driven shoreline change scenarios; (b) to explore how forecasted changes could impact people as well as other species; and (c) to develop a modeling framework capable of considering (i) physical drivers and biogeomorphological responses that span spatial and temporal scales and (ii) uncertainty in predicted outcomes. We use Fire Island—a barrier island off the coast of Long Island, New York, USA (Figure 1)—as a pilot location for this work.

2. Materials and Methods

2.1. Study Area on Fire Island, New York

Fire Island is centrally located in a barrier system that spans the south shore of Long Island, New York (Figure 1). The approximately 50-km barrier island is a patchwork of state, county, and federal parks—including the Fire Island National Seashore—interspersed with private lands and is, therefore, a mix of anthropogenically modified segments (e.g., with residential communities, roads, and infrastructure near the primary dune-line) and protected segments with minimal development. The island is oriented east-northeast, and the predominant southerly wave direction drives net longshore transport from the east to the west (Taney, 1961). Fire Island is considered microtidal and wave-dominated (Hayes, 1979). Three inlets are present in the study area that carry sediment from the ocean to the back-barrier to sustain the marsh system (Leatherman, 1985, 1989), and historic records suggest

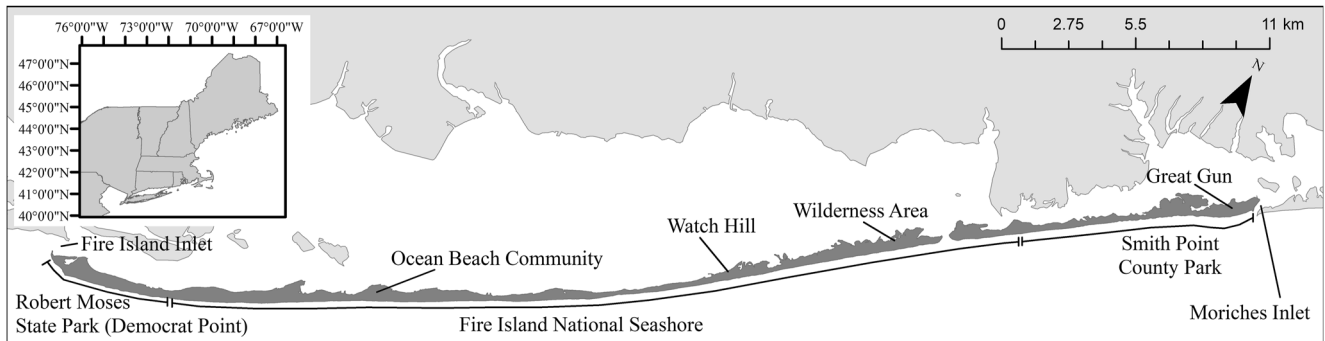


Figure 1. Fire Island study area, located off the coast of Long Island, New York, USA.

overwash is an important contributor to sustained landward migration of the island (Lentz et al., 2013). Generally, relatively narrow beaches and high dunes (some as tall as 11 m) characterize the central-eastern segment of the island, whereas wider beaches and lower dunes (averaging 4.5 m) are found to the west (Hapke et al., 2013).

Erosion of a lobe of Pleistocene outwash sediment located offshore of Watch Hill (Figure 1; reviewed in Lentz et al. [2013]) has supplied abundant well-sorted medium to fine-grained sand to the inner-continental shelf down-drift to the west. These sediments have been reworked to form a series of shoreface-attached sand ridges west of Watch Hill, and the onshore flux of sediment from these ridges may be supplying the sediment volume required for maintaining island stability west of Watch Hill (Schwab et al., 2000). East of Watch Hill, the modern reworked sediment deposit is relatively thin or absent on the inner continental shelf and lower shoreface. Here, the only sediment available to supply the island is from updrift erosion and the relatively coarse-grained, less mobile Pleistocene material offshore. As a result, the barrier island migrates landward at a relatively rapid rate (Schwab et al., 2000). Sediment budgets conducted for the south shore of the Long Island barrier system estimate that an average of approximately 200,000 m³/yr of sediment is leaving the system at Fire Island Inlet than is entering the system at Moriches Inlet (reviewed in Lentz et al. [2013]). The lack of landward migration along the western reach of the island supports the theory that alongshore contributions from the ridges may serve as a sediment source supplying the western reach with ample material to maintain position and balance the system losses at Fire Island Inlet (reviewed in Lentz et al. [2013]).

Documented average net shoreline change rates for Long Island have been accretional at 0.08 ± 0.2 m/yr (1830–2007) and 0.8 ± 0.09 m/yr (1983–2000; Hapke et al., 2010). However, true rates of shoreline erosion may be masked by current coastal management practices (Armstrong & Lazarus, 2019). According to Rice (2015), the majority of ocean-front shoreline along Fire Island has directly or indirectly experienced beach replenishment (also known as beach fill or renourishment) in the last 10–15 years, and approximately 24 small areas of the coastline were armored with hard shoreline stabilization structures as of 2015. Additionally, evidence indicates that the back-barrier (bay-side) shoreline is experiencing widespread erosion that is exacerbated by the presence of marinas and bulkheads (Nordstrom & Jackson, 2005). Furthermore, over the last few decades, the northeastern United States has experienced relative SLR rates three to four times higher than the global average (Boon, 2012; Dupigny-Giroux et al., 2018; Ezer & Corlett, 2012; Goddard et al., 2015; Kopp, 2013; Sallenger et al., 2012; Sweet et al., 2017; Sweet & Park, 2014), and continued higher than global average rates are projected in the future (Dupigny-Giroux et al., 2018; Sweet et al., 2017).

2.2. Piping Plovers: An Umbrella Species for Beach Ecosystems

We use the piping plover (*Charadrius melodus*) as an indicator species for understanding the implications of biogeomorphological change for non-human species on Fire Island because of this bird's reliance on low-lying coastal habitats and rapid population-level response to habitat change (Cohen et al., 2009; Robinson et al., 2019; Zeigler, Gutierrez, et al., 2019). This species also has demonstrated value as an umbrella conservation species for other sympatric species, such as American oystercatchers (*Haematopus palliatus*), black skimmers (*Rynchops niger*), and least terns (*Sterna antillarum*; Maslo et al. [2016]). Furthermore, because nesting pairs tend to select low-lying regions prone to overwash (Zeigler, Gutierrez, et al., 2019; Zeigler et al., 2021), identifying where

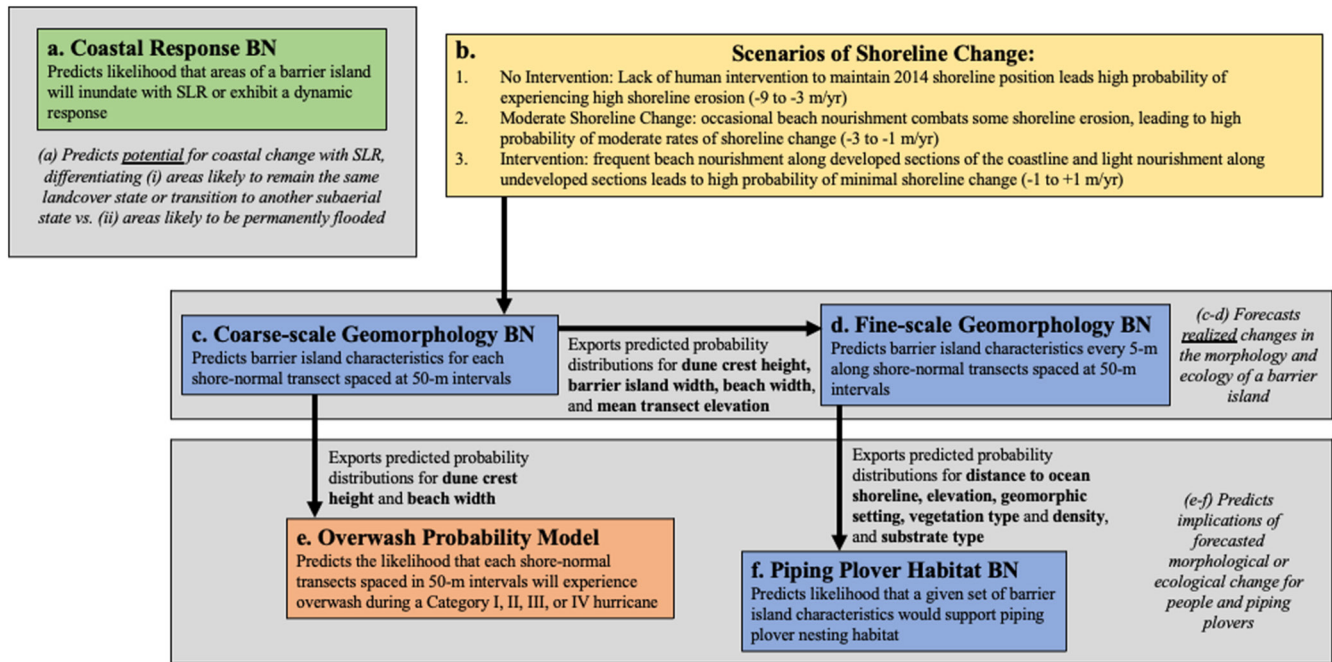


Figure 2. Conceptual diagram of models used in this study: The Coastal Response Bayesian Network (BN; (a) was used as a discrete model to evaluate the potential for sea-level rise (SLR)-driven inundation on Fire Island, given initial elevation and landcover type. Under three scenarios of shoreline change (b), the Coarse-scale Geomorphology BN (c) was used to forecast likely realized changes along the cross-section of the island (e.g., barrier island width, beach width). Outputs, in the form of probability distributions, were passed to the Fine-scale Geomorphology BN (d) to predict associated changes to the barrier island for higher resolution variables (e.g., geomorphic setting, vegetation type). Finally, outputs from these two geomorphology BNs were used as inputs in an overwash probability model (e) and the Piping Plover Habitat BN (f) to forecast the implications of biogeomorphological changes on Fire Island for people and the federally threatened piping plover. Connections among individual models, through shared variables, are shown with black arrows.

habitat is most suitable can also help identify areas where infrastructure, recreation, and human access may be more vulnerable to overwash processes.

Piping plovers are migratory shorebirds with discrete breeding populations on the Atlantic coast, the Great Lakes, and the Northern Great Plains of Canada and the United States where they are considered either federally threatened or endangered (U.S. Fish and Wildlife Service, 1996). Here, we consider the federally threatened Atlantic coast population. These birds typically establish nests in washover features, backshore areas, and low elevation dune complexes with sandy substrates and minimal vegetation (U.S. Fish and Wildlife Service, 1996; Cohen et al., 2009; Maslo et al., 2011; Zeigler et al., 2021). Breeding pairs lay up to four eggs in small depressions in the sand beginning in May, and precocial chicks hatch after approximately 27–30 days of incubation (U.S. Fish and Wildlife Service, 1996). Adults and chicks forage along low-energy ocean- or bay-side intertidal zones and ephemeral pools, where they consume marine worms, arthropods, mollusks, and crustaceans (U.S. Fish and Wildlife Service, 1996). Chicks fledge by August when adults and fledglings begin migrating back to wintering grounds in the Caribbean and the southeastern Atlantic and Gulf of Mexico coasts (U.S. Fish and Wildlife Service, 1996).

2.3. Bayesian Networks

In order to holistically understand biogeomorphological change and its implications on Fire Island, we employed five probabilistic models that predicted dynamic change likelihood, biogeomorphological characteristics, overwash probability, and piping plover habitat availability (Figure 2). Four of the five probabilistic models used are Bayesian networks (BN). In general, a BN is a directed acyclic graph composed of nodes and edges that organize knowledge about a system. Nodes represent variables describing relevant system components and are further broken down into discrete characteristics or, for continuous variables, discretized bins. Edges connect nodes to convey dependencies, correlations, or causal influences among nodes (Korb & Nicholson, 2004). Using observational and modeled data, probability distribution functions (PDF) are calculated for each node according to the

Bayes Theorem, where a PDF is a statistical expression that defines the likelihood of an outcome for a discrete random variable (Korb & Nicholson, 2004). The set of all possible node-value combinations forms a conditional probability table that underlies a 'trained' BN. Once trained, the BN can be used to predict the probability of a specific node value. In such cases, the BN is used to determine the probability of observing specific states for nodes in which the true state is unknown, with epistemic uncertainty represented in the uniformity of the predicted conditional probabilities (Korb & Nicholson, 2004).

2.3.1. Coastal Response Bayesian Network

First, we used the Coastal Response BN (Lentz et al., 2015a, 2016; Figure S1 in Supporting Information) to evaluate Fire Island's probability of exhibiting a dynamic coastal response to SLR, defined as the likelihood that landcover will remain in its existing state or transition to a new non-submerged state in response to future sea levels. Landcover types considered include marsh, beach, rocky, forest, and developed (based on McGarigal et al., 2017). Examples of a dynamic response include (a) a forest transitioning to a beach or (b) a marsh remaining a marsh. Results are viewed as an inverse relationship, wherein an area that has a low probability of exhibiting a dynamic response has a high inundation probability (i.e., inundation probability = 1 – dynamic response probability). In the original publications describing this model and its results (Lentz et al., 2015a, 2016), predictions were generated over a 38,000 km² region from Maine to Virginia, the USA, for future sea level scenarios in the 2020s, 2030s, 2050s, and 2080s (Lentz et al., 2015b). Two probabilistic outcomes were generated at 30 × 30 m resolution, bounded by the 10-m elevation contour inland to –10 m offshore: (a) adjusted elevation relative to the projected sea level and (b) dynamic response probability. These outcomes were influenced by the values of the input variables, which included projected SLR, vertical land motion, elevation, and landcover type (Table 1; Figure S1). Dynamic response probability was estimated by coupling the predicted adjusted elevation ranges with expert knowledge on the response of the landcover types.

The SLR scenario used in this model was developed as part of a prior study (Lentz et al., 2016) and differed from scenarios used in the other probabilistic models in this study. The coastal response SLR scenario estimated the increase from present day levels given three component processes: ocean dynamics (generated from 24 Coupled Model Intercomparison Project Phase 5; CMIP5 models; Taylor et al. [2012]), ice melt (as estimated by Bamber & Aspinall, 2013 for the two Antarctic Ice Sheets and by Marzion et al., 2012 and Radic et al., 2013 for glaciers and ice caps), and global land water storage (based on Church et al. [2013]). Estimated percentiles of these three components were aggregated to provide an SLR scenario and corresponding uncertainty for a given time step and resulted in the following decade-based ranges: 2020s (0–0.25 m), 2030s (0.25–0.5 m), 2050s (0.5–0.75 m), and 2080s (0.75–2 m). These ranges generally align well with the most likely or highest probability scenarios used in the 2018 National Climate Assessment and as reported in Sweet et al. (2017), albeit without vertical land movement effects. Instead, local vertical land movement rates driven by glacial subsidence were incorporated using long term GPS CORS station data (Sella et al., 2007) as well as long term tide gauge information (Zervas et al., 2013) in a separate node (Figure S1). For simplicity, these data were kept as time independent in the BN, meaning that, for a given decade, the most likely relative SLR scenario range was selected and applied. Elevation values were based on 2010 conditions and obtained from the National Elevation Dataset at 1/9 and 1/3 arc-second resolutions and Coastal Relief Model (NOAA, 2014). Elevation was converted from the North American Vertical Datum to mean high water using VDatum conversion grids (National Ocean Service, 2012). Adjusted elevation was calculated by using a probabilistic implementation of a deterministic equation that subtracted SLR and vertical land motion from 2010 elevation.

Bayesian inference was used to train the model on the geospatial co-occurrence of elevation and landcover datasets and their inherent correlation. The dynamic response probability assigned to different landcover types compared adjusted elevation with the inundation thresholds specific to the initial landcover type. This landcover-specific likelihood was based on a synthesis of published studies extensively documented in Lentz et al. (2015a, 2016). Expert knowledge was applied to fill information gaps (e.g., rocky land cover types).

The results evaluated in the present study were previously published as part of the regional analysis, and the full methodology and results can be reviewed in Lentz et al. (2016, 2015b). To understand the likelihood of dynamic change at our study site, we clipped and evaluated regional results for predicted SLR by the 2050s (+0.5 to +0.75 m; Lentz et al. [2015b]) to the subaerial footprint of Fire Island, whereby the boundaries of the study area were the ocean, inlet, and back-barrier shorelines observed in 2014/2015 (Figure 1; Sturdivant et al., 2019). All spatial processing and analyses were conducted in ArcGIS version 10.6.1 (ESRI). The Coastal Response BN was

Table 1
Input and Predictive Output Variables Used in Bayesian Networks

Bayesian network	Source	Input variables	Output (predictive) variables	Spatial scale ^a	Error rate ^b
Coastal Response	Lentz et al., 2015, 2016	(1) Projected sea level (m) (2) Vertical land motion (m) (3) Elevation (m) (4) Land cover type	(1) Adjusted elevation with respect to SLR (m) (2) Coastal response likelihood	30 × 30 m raster cells	n/a
Coarse-scale Geomorphology	Adapted from Gutierrez et al., 2015	(1) Shoreline change rate (m/yr) (2) Distance to inlet (m) (3) Beach height (m) (4) Distance from shoreline to dune (m) (5) Frequency of beach nourishment (6) Level of human development (7) Type of shoreline stabilization	(1) Dune height (m) (2) Barrier island width (m) (3) Beach width (m) (4) Mean transect elevation (m)	Transects oriented perpendicularly to the shoreline and spaced 50-m apart.	23.4%–54.8%
Fine-scale Geomorphology	Adapted from Gutierrez et al., 2015; Gutierrez et al., in press	(1) Dune height (m) (2) Barrier island width (m) (3) Beach width (m) (4) Mean transect elevation (m)	(1) Distance to dune (m) (2) Distance to shoreline (or ocean; m) (3) Elevation (m) (4) Geomorphic setting (5) Vegetation type (6) Vegetation density (7) Substrate type	Points spaced every 5 m along each transect.	27.2%–45%
Piping Plover Habitat	Zeigler et al., 2021	(1) Beach width (m) (2) Distance to ocean (m) (3) Elevation (m) (4) Geomorphic setting (5) Vegetation type (6) Vegetation density (7) Substrate type	(1) Probability of being piping plover habitat (Habitat availability)	5 × 5 m raster cells	18%

Notes. ^aSpatial scale denotes the resolution over which predictions were made. ^bError rates for the Coarse-scale and Fine-scale Geomorphology BNs were calculated through 5-fold cross-validation, where multiple variables were hindcast simultaneously. Error rates were calculated for each output variable, and we report the range of error rates across variables. Details in Gutierrez et al. (in review). Error rate for the Piping Plover Habitat BN was measured as the percentage of actual nests that were incorrectly predicted to be a random point and vice versa in 10-fold cross-validation (Zeigler et al., 2021).

not connected to any other model used in this study nor did it consider the scenarios used to inform the other models (Figure 2). Instead, this BN offered a first order analysis of where SLR-driven change can be expected on Fire Island.

2.3.2. Geomorphology Bayesian Networks

Because the Coastal Response BN does not indicate the nature of dynamic change (only its likelihood), we adapted two additional BNs from Gutierrez et al. (2015) to explore more specific SLR-driven changes to the island's ocean shoreline, geomorphological, and vegetation characteristics by 2050. Here, each geomorphology BN addressed geomorphological responses at different spatial scales (50 m vs. 5 m), which ensured more consistency in predictions and improved computational efficiency.

The first BN—the Coarse-scale Geomorphology BN—considers variables best measured across a barrier island's cross-section (Table 1; Fig. S2 in Supporting Information), such as distance to the inlet, dune height, barrier island width, beach width, mean elevation, and distance from the shoreline to dune crest. We also included an input variable for shoreline change rate after Gutierrez et al. (2014). This variable, measured in meters per year,

could be positive (accretion) or negative (erosion) and reflects net changes in shoreline position related to both SLR and human response (e.g., beach nourishment, hard stabilization, etc.). Finally, we incorporated three categorical input variables to capture anthropogenic modification to the barrier island across each cross-section: the presence of (a) beach nourishment ('nourishment'), (b) erosion management structures ('construction'; e.g., a seawall), and (c) development (e.g., residential communities). Network structure was such that forcing variables (shoreline change rate, distance to inlet, nourishment, development, construction) were parent nodes to variables that describe basic characteristics of a barrier island cross-section (barrier island width, mean elevation, distance to dune crest, dune height, beach width, beach height; Figure S2).

The second BN—the Fine-scale Geomorphology BN—considers variables best measured at a higher resolution at discrete points along a barrier island's cross-section (Table 1; Figure S3 in Supporting Information). Here, child variables present in the Coarse-scale Geomorphology BN (barrier island width, mean elevation, distance to dune, dune height, beach width, beach height) are now parent nodes to higher resolution variables (distance to shoreline, geomorphic setting, elevation, substrate type, vegetation type, and vegetation density). Additional information about these BNs, including validation and skill testing, can be found in Gutierrez et al. in press.

The BNs were developed in Netica version 6.05 (Norsys™), where they were trained using an expectation-maximization algorithm (EM) to compute the posterior probability for each variable (Dempster et al., 1977; Lauritzen, 1995). We derived prior probability distributions by sampling characteristics on Fire Island for each variable from geospatial products derived from lidar and orthoimagery captured in 2010, 2012, and 2014/2015 (Sturdivant et al., 2019; Zeigler, Sturdivant et al., 2019) as well as from datasets associated with the U.S. Geological Survey's National Assessment of Coastal Change Hazards (Doran et al., 2017; Himmelstoss et al., 2010). Variables contained in the Coarse-scale Geomorphology BN were sampled along transects spanning the cross-section of Fire Island spaced in 50-m intervals, while variables contained in the Fine-scale Geomorphology BN were sampled at points spaced in 5-m intervals along each transect. This range of dates captures pre- and post-storm variability in biogeomorphological states found on Fire Island. Data from 2010 to 2014 represent more typical Fire Island conditions, which may include remnants of other, less extensive storm impacts. Data from 2012 capture conditions shortly after Hurricane Sandy made landfall in this region. Shoreline change rates associated with each transect were derived from the U.S. Geological Survey's National Assessment of Shoreline Change (Hapke et al., 2010; Himmelstoss et al., 2010) and represent the rate of change of shoreline positions over the past ~150 years. We used the linear regression rates of long-term shoreline change calculated from a set of 6–10 historical shorelines spanning 1845–2000.

As in any BN, the prior probability distributions established relationships and associations among variables using historical data. As an illustrative example, refer to Figure S4 in Supporting Information. This figure shows the PDFs for variables in the Coarse-scale Geomorphology BN that were associated with high rates of shoreline erosion in the historical training data (e.g., around Robert Moses State Park; Figure 1). These areas were unlikely to be developed or to be managed with beach nourishment or shoreline stabilization structures (Figure S4). Areas experiencing high rates of shoreline erosion also tended to be closer to inlets (<5 km); have a distance between the shoreline and primary dune line between 100 and 300 m; have a mean transect elevation between 0 and 2 m, and have a beach height between 1 and 3 m (Figure S4). When used for forecasting purposes, the BNs used in this study calculate likelihoods for the possible values of variables whose true values are unknown (i.e., the output variables) based on the associations among variable values in the training data. In this way, underlying processes like sediment supply and anthropogenic modifications to the landscape are inherently considered in the BN through the training data and associated historical observations and trends.

Once trained, data analysis in the BNs was conducted using Matlab codes (version 9.5) based on those developed in Python by Fienen and Plant (2015). To forecast future biogeomorphological conditions on Fire Island, we started by specifying a scenario-based shoreline change rate and beach nourishment frequency in the Coarse-scale Geomorphology BN (see Section 2.4 for a description of scenarios; Figures S5–8 in Supporting Information). We also specified values for each transect for the remaining anthropogenic modification variables, distance to the inlet, beach height, and distance from the shoreline to the dune crest according to initial conditions in the 2014/2015 training dataset. Associations among those initial conditions in the trained Coarse-scale Geomorphology BN produced predicted probability distributions for the output variables dune height, barrier island width, beach width, and mean transect elevation (Figures S6–8). Probability distributions for these output variables for each transect were then used as inputs in the Fine-scale Geomorphology BN. This BN produced corresponding

probability distributions for distance to dune crest, distance to the shoreline (or ocean), elevation, geomorphic setting, vegetation type, density, and substrate type for each point on each transect. By linking the models in this way, the two geomorphologies BNs allowed us to specify initial geomorphological conditions, as well as shoreline change and management scenarios to then forecast likely future biogeomorphological conditions on Fire Island based on patterns observed in the historical training data.

2.3.3. Piping Plover Habitat Bayesian Network

Finally, we used the Piping Plover Habitat BN to evaluate the implications of biogeomorphological evolution at Fire Island on piping plovers. This network was originally developed, described, and evaluated in Zeigler et al. (2021). This prior work used a dataset of landscape characteristics at piping plover nests and random points located in the species' New York-New Jersey recovery unit (Fire Island and the Rockaway Peninsula, New York; Long Beach and Pullen islands, New Jersey). This dataset contained 335 points comprised of 178 nest locations and 157 random points (Sturdivant et al., 2016; Thieler et al., 2016; Zeigler et al., 2017). Characteristics for the variables geomorphic setting, substrate type, vegetation type, and vegetation density were observed *in-situ* (detailed variable definitions in Zeigler, Sturdivant et al., 2019; Zeigler et al., 2017). Nests and random points were also characterized *ex-situ* in terms of beach width, elevation, least-cost path distance to areas with moist substrates on low-energy shorelines (henceforth, 'distance to MOSH'), and Euclidean distance to the ocean shoreline (referenced to mean high water; henceforth, 'distance to ocean') using remotely sensed lidar and orthoimagery. Detailed processing methods and spatial datasets are published separately (Sturdivant et al., 2019; Zeigler, Sturdivant, & Gutierrez, 2019). Using ArcGIS Toolbox 10.4.1 (ESRI™), we assigned values from the nearest pixel centroid in each raster layer to the presence/absence dataset points. Variables considered in this study were identified as known or suspected drivers of piping plover habitat selection based on peer-reviewed literature and expert opinion (reviewed in Zeigler et al. [2021]).

Using this New York-New Jersey presence/absence dataset, a recovery unit-specific habitat selection BN was developed according to a data-driven approach (Zeigler et al., 2021). The dataset was used to fit a BN in the R package *bnlearn* 4.5 with the score-based hill-climbing learning algorithm and the Bayesian Information Criterion (BIC) score (Scutari, 2010), focused on the single binary output variable 'habitat availability'. This 'greedy' algorithm iteratively adds, removes, and reverses the direction of edges between nodes to find the optimal network structure with the lowest BIC score given the data (Scutari, 2010). Network inference was also partially constrained based on previous knowledge of barrier island dynamics and piping plover habitat selection to enhance the structural learning process (Chen & Pollino, 2012; Zeigler et al., 2021). The output variable 'habitat availability' gives the probability that a given combination of landscape characteristics will support the piping plover habitat. The final BN structure and probability distributions are illustrated in Figure S9 in Supporting Information.

We used the Piping Plover Habitat BN here for forecasting purposes, wherein we determined the likelihood that Fire Island would support piping plover habitat given predicted biogeomorphological conditions under future shoreline change scenarios. We linked the two geomorphology networks through shared variables (as described in the previous section) to predict probability distributions for distance to the shoreline (or ocean), elevation, geomorphic setting, substrate type, and vegetation type and density at each 5-m point along shore-normal transects spaced at 50-m intervals along Fire Island. These output probability distributions were then passed as inputs into the Piping Plover Habitat BN to ultimately forecast future piping plover habitat availability under three scenarios of shoreline change (Section 2.4). Thus, scenario and initial transect conditions set in the Coarse-scale Geomorphology BN (Figures S6-8) propagated through to the Piping Plover Habitat BN to assess the implications of biogeomorphological change (Figure 2). The mechanics of linking the geomorphology BNs with the Piping Plover Habitat BN, including an evaluation of error rate and uncertainty propagation, are described in more detail in Gutierrez et al. (in press).

In the present study, we modified the Piping Plover Habitat BN structure described in Zeigler et al. (2021) for forecasting purposes by removing the variable for distance to MOSH. Moist substrate habitats (e.g., bay and inlet shorelines, ephemeral pools) offer important foraging habitats for piping plovers and their chicks prior to fledging (Cohen & Fraser, 2010; Loegering, 1992; Maslo et al., 2012) and are an important factor in piping plover habitat selection patterns in certain regions (Zeigler et al., 2021). However, the geomorphology BNs do not currently model forecasted changes to the back-barrier shoreline or smaller ephemeral water bodies, and we, therefore, removed the distance to MOSH variable to reduce the error that would be introduced with the incorrect placement

of MOSH locations. Gutierrez et al. (in press) examined the impact of not including this variable in the validation of the linked geomorphology-piping plover habitat framework. They found that the BN with the variable distance to MOSH predicted that 23.8% of Fire Island would support piping plover habitat compared to 27.4% predicted by the model without the MOSH variable. Therefore, without a variable for access to foraging habitat, BNs used in the present study may over-predict habitat availability.

2.3.4. Probabilistic Overwash Model

After initially evaluating results from the two geomorphology and the Piping Plover Habitat BNs, we added an analysis using a fifth probabilistic model to further explore the likelihood of storm-driven morphological conditions not captured by the BNs. Although ‘washover’ is a geomorphic feature considered in the Fine-scale Geomorphology BN, we found that this BN never predicted washover as the most likely geomorphic setting. This is because washover is present over a much smaller area of Fire Island compared to settings like backshore and barrier interior (as reflected in the training data) and is therefore probabilistically less likely to occur. We, therefore, used the fifth model to evaluate the probability of overwash processes during extreme storms (Category I-IV hurricanes), given the new dune and beach width conditions forecasted by the Coarse-scale Geomorphology BN under each scenario (Section 2.4). This model, including simulated storm scenarios, is documented in Birchler et al. (2014). The probability of overwash (pOW) was modeled according to Equation 1:

$$pOW = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{\infty} \hat{e}^{-\left(t-\mu\right)^2/2\sigma^2} dt, \quad (1)$$

where $t-\mu$ is the mean difference between the extreme water level (dependent on the hurricane scenario) and dune crest elevation, and the variance of the difference (σ^2) is the sum of the variances of the inputs. pOW then becomes the probability that the 98% exceedance level—as defined in Stockdon et al. (2007)—minus the dune crest elevation is greater than 0, indicating where overwash processes are likely to occur to produce a washover feature. For this analysis, we used an overwash model previously parameterized with conditions, water levels, and storm scenarios for the U.S. mid-Atlantic coast (Birchler et al., 2014). Overwash probabilities were calculated based on dune height and beach width conditions predicted by the Coarse-scale Geomorphology BN along each shore-normal transect spaced in 50-m intervals. The probability of overwash generated by this fifth model does not influence the Piping Plover Habitat BN (Figure 2); however, an increased probability of overwash suggests the potential for additional piping plover habitat to form in the event of a storm given the new underlying morphological conditions of the beach in 2050.

2.4. Forecast Scenarios

For the geomorphology and Piping Plover BNs, we explored likely biogeomorphological conditions on Fire Island for the year 2050 under three scenarios, where we assumed that SLR accompanied by varying levels of human intervention would influence the expression of shoreline change on the landscape. We included five bins for shoreline change rates, ranging from erosion at -9 m/yr to accretion at $+30$ m/yr (Figures S5-8 in Supporting Information). Scenarios were specified directly in the Coarse-scale Geomorphology BN (Figure 2) through the variables ‘shoreline change rate’ and ‘beach nourishment’ (Figures S6-8), ultimately propagating through to the Fine-scale Geomorphology and Piping Plover Habitat BNs when BNs were linked through shared variables. Scenario specifications in the Coarse-scale Geomorphology BN included the following:

1. No Intervention (Figure S6): we assumed no human intervention to maintain the current shoreline position. Here, the shoreline change rate bin with the highest rate of erosion (-9 to -3 m/yr) had the highest probability of occurring (Figure S5). All barrier island characteristics were forecast by setting beach nourishment, (future) development, and construction to ‘none’. All remaining input variables were specified based on each transect's initial conditions as observed in 2014/2015 remotely sensed imagery. In general, all transects tended to behave like the cross-sections around Robert Moses State Park (Figure 1; Figure S4), which has historically experienced high rates of shoreline change and minimal stabilization efforts
2. Moderate shoreline change (Moderate SLC; Figure S7): we assumed that some human intervention to maintain the shoreline position would result in moderate rates of shoreline change across Fire Island. Here, the shoreline change rate bin with lower rates of shoreline erosion (-3 to -1 m/yr) had the highest probability

- of occurring (Figure S5). We assumed that all transects would experience 'occasional' beach nourishment to combat erosion. All remaining input variables (including development and construction) were specified based on each transect's initial conditions as observed in 2014/2015 remotely sensed imagery
3. Intervention (with minimal shoreline change; Figure S8): we assumed that high levels of human intervention would maintain the shoreline in its current position. We specified this scenario by modifying the shoreline change rate such that minimal shoreline change (-1 to $+1$ m/yr) had a 100% probability of occurring (Figure S5) and indicating 'frequent' beach nourishment (Figure S8). All other input variables were specified according to initial conditions observed in 2014/2015 remotely sensed imagery. We maintained the shoreline at its 2014/2015 position for the entire island and assumed morphological conditions would also remain the same for transects that had moderate or heavy human development in 2014/2015 remotely sensed imagery. Where human development was not present or was classified as "light," we allowed the geomorphology BNs to predict future morphology (e.g., dune crest height, beach width, elevation) without changing shoreline position

Although we forecasted a change in the position of the ocean shoreline in the No Intervention and Moderate SLC scenarios by setting a probability distribution for shoreline change rate, the geomorphology models were not designed to accurately simulate changes to the back-barrier shoreline nor the complex processes that allow for back-barrier marsh evolution. Therefore, we retained the back-barrier shoreline position observed in the 2014 lidar as the rear boundary of our analysis of forecasted change under all three scenarios. We describe why this assumption was reasonable for Fire Island in the Discussion.

2.5. Analysis of Results and Comparison to Current Conditions

For context, the results of these scenarios were compared to characteristics observed on Fire Island as of 2014/2015. Observed biogeomorphological characteristics and piping plover habitat availability were derived for the study area using remotely sensed lidar captured in 2014 (NOAA, 2015) and orthoimagery captured in 2015 (available upon request from J. Fraser, Virginia Tech). The baseline position of the ocean shoreline was based on 2014 conditions in the lidar dataset. Spatial datasets were processed as described in Zeigler, Sturdivant et al. (2019) and are available in Sturdivant et al. (2019). To determine piping plover habitat availability, we interpreted lidar and orthoimagery to produce raster layers for each variable present in the Piping Plover Habitat BN as described in Zeigler, Sturdivant, et al. (2019). Layers were combined such that each $5\text{ m} \times 5\text{ m}$ landscape cell had a value for each variable, and we associated a probability that a given landscape cell contained nesting habitat with the Piping Plover Habitat BN according to the methodology presented in Zeigler et al. (2017).

As all models used in this work are probabilistic, we defined probability thresholds according to the Intergovernmental Panel on Climate Change's likelihood scale (Mastrandrea et al., 2010). Under this scale, an event is *likely* to occur or a condition is *likely* to be present when the probability (p) of a specific outcome is ≥ 0.66 . For example, a given landscape cell is likely to support piping plover habitat or to exhibit a dynamic coastal response when $p \geq 0.66$ according to the Piping Plover Habitat and the Coastal Response BNs, respectively. An event is *unlikely* to occur or a condition is *unlikely* to be present when $p \leq 0.33$. For instance, a given landscape cell is unlikely to support a piping plover habitat or to exhibit a dynamic coastal response when $p \leq 0.33$ according to the respective networks. When $0.33 < p < 0.66$, we considered predictions to be uncertain, wherein an event or condition is *as likely as not* to occur. For many barrier island characteristics, we also report the most likely bin and value range for that characteristic. For example, the continuous variable beach width was discretized into four possible bins. If the Coarse-scale Geomorphology BN predicted a 90% probability that beach width at a particular transect would be in bin 1, we reported that that transect was likely to have a beach width between 0 and 30 m (Figure S2) and that that prediction had a relatively high degree of certainty. However, if the model predicted a 25% probability for each of the four bins used to describe beach width (i.e., a uniform probability distribution), a most likely value for beach width on that transect could not be determined, and we concluded that the forecasted beach width value was uncertain or unknown.

Due to variability in the spatial resolution of each BN, we present results as either an area coverage or based on the number (or percentage) of transects. Predictions made by the Coastal Response BN are presented as a spatial coverage with 30 m resolution, according to the original study (Lentz et al., 2016). The Coarse-scale Geomorphology BN's predictions were made for each shore-normal transect, and we report dune height and

Table 2

Response Regimes Following Passeri et al. (2020) Observed for 1,061 Shore-Normal Transects Along Fire Island, New York

Regime type	Definition	# (%) of transects where prediction made		
		Intervention	Mod SLC	No intervention
Keeping Pace/Aggradation	Transect maintained or increased in width and elevation	910 (88%)	114 (41%)	57 (38%)
Narrowing	Transect decreased in width but maintain/gained elevation	22 (2%)	99 (35%)	56 (37%)
Flattening	Transect decreased in elevation but maintain/gained width	100 (10%)	47 (17%)	15 (10%)
Deflation	Transect decreased in both width and elevation	1 (<1%)	19 (7%)	24 (16%)
<i>Transects where no elevation or width prediction made (uniform probability distribution)</i>		<i>28 (3% all transects)</i>	<i>782 (74%)</i>	<i>909 (86%)</i>

Notes. Forecasts for the year 2050 were made in scenarios that assumed (i) human intervention to maintain the current shoreline position (e.g., through beach nourishment; ‘Intervention’); (ii) moderate shoreline change resulting from some human intervention to stabilize the shoreline (‘Mod SLC’); and (iii) high rates of shoreline change resulting from a lack of human intervention to stabilize the shoreline (‘No Intervention’). Because predictions became increasingly uncertain as scenario-based shoreline change rates increased, we report the percentage of transects for which predictions could not be made for each regime type.

beach width—and changes in these characteristics—as numbers or percentages of transects with no additional post-processing. Predictions made by the Fine-scale Geomorphology and Piping Plover Habitat BNs were made at 5-m intervals along each transect. To analyze and report these results, we extrapolated values to create a surface for each variable using the Euclidean Allocation tool in ArcGIS (5-m cell size; planar distance method) and clipped surfaces to the 2014/2015 shoreline boundaries (Figure 1; Sturdivant et al. [2019]). Surfaces were created for the most probable geomorphic setting, substrate type, vegetation type, and discretized elevation bin as well as for the probability of piping plover habitat availability.

3. Results

3.1. Barrier Island Evolution—Physical Characteristics

We evaluated biogeomorphic change on Fire Island as a function of shoreline change scenarios, where we forced an increasing probability of larger rates of ocean shoreline change from the Intervention to the No Intervention scenarios. The mean shoreline change rates associated with these forced assumptions were 0, −2.37, and −4.71 m/year for the Intervention, Moderate SLC, and No Intervention scenarios, respectively, with negative values indicating erosion. Using these mean shoreline change rates and multiplying by 36 (i.e., the number of projection years from initial conditions in 2014/2015 to forecasted predictions for 2050) resulted in an estimated landward retreat of the island by 0, 85, and 170 m, respectively. Here, a lack of shoreline change under the Intervention scenario is grounded on the assumption that humans will try to aggressively combat shoreline erosion through beach nourishment and structural engineering.

With shoreline changes of those magnitudes, high uncertainty was prevalent in our predictions of barrier island evolution in response to SLR. For many transects, the Coarse- and Fine-scale Geomorphology BNs predicted a uniform probability distribution for several variables, and distributions tended to become more uniform with increasing rates of shoreline change. This was particularly evident for predictions of mean barrier island transect elevation and barrier island width (Table 2) as well as beach width, elevation, and dune height (Table 3). The number of transects with uncertain predictions increased from 3% to 28% of all transects under the Intervention scenario to 74%–78% under the Moderate SLC scenario to 86%–88% under the No Intervention scenario, depending on the variable of interest (Tables 2–3). In addition, although the Coastal Response BN was not governed by the same scenarios as the geomorphology BNs, this model predicted that 57% of the island was as likely as not to exhibit a dynamic response to SLR. In other words, over half of the island is as likely to inundate as it is to dynamically respond and will therefore have an uncertain response to SLR (Table 4; Figure 1).

Where predictions could be made (i.e., the probability distribution for a given variable was not uniform and one bin had a higher probability of occurring over the others), the geomorphology BNs predicted an increasingly flatter and/or narrower island as scenarios included higher rates of shoreline change. The median barrier island width, which was 408 m in 2014/2015, declined to 320 and 236 m under the Moderate SLC and No Intervention

Table 3
Forecasted Changes for the Year 2050 on Fire Island Compared to Observed 2014/2015 Conditions

	Intervention		Moderate SLC		No intervention	
	<i>Area (km²) or number of transects</i>	<i>Percentage of total area or transects</i>	<i>Area (km²) or number of transects</i>	<i>Percentage of total area or transects</i>	<i>Area (km²) or number of transects</i>	<i>Percentage of total area or transects</i>
<i>Elevation (area, km²)</i>						
No change	6.6	33%	5.1	25%	4.5	22%
Decreased elevation	8.6	43%	8.0	40%	8.5	43%
Increased elevation	4.9	24%	6.9	35%	7.0	35%
<i>Dune Height (number of transects)</i>						
No change	314	30%	69	7%	26	2%
Decreased elevation	100	9%	161	15%	96	9%
Increased elevation	263	25%	12	1%	17	2%
Uncertain change	377	36%	812	77%	915	87%
<i>Beach Width (number of transects)</i>						
No change	418	40%	39	4%	7	1%
Became narrower	12	1%	0	0%	0	0%
Became wider	224	21%	190	18%	124	12%
Uncertain change	400	38%	825	78%	923	88%
<i>Geomorphic Setting (area, km²)</i>						
No change	13.2	64%	9.0	44%	6.0	29%
Change from one subaerial setting to another	5.6	27%	7.2	35%	6.1	29%
Change from subaerial to water	0.2	1%	4.3	21%	8.5	42%
Change from water to subaerial	0	0%	0	0%	0	0%
Uncertain change	1.7	8%	0	0%	0	0%

Notes. Forecasts were made in scenarios that assumed (i) human intervention to maintain the current shoreline position (e.g., through beach nourishment; ‘Intervention’); (ii) moderate shoreline change resulting from some human intervention to stabilize the shoreline (‘Moderate SLC’); and (iii) high rates of shoreline change resulting from a lack of human intervention to stabilize the shoreline (‘No Intervention’). Dune height and beach width were measured along shore-normal transects spaced in 50-m intervals, and we report the number and percentage of transects that experienced change (or lack thereof). Transects for which there were no most likely values for beach width or dune crest elevation (i.e., uniform probability distributions) were tallied as ‘uncertain change’. Elevation and geomorphic setting were measured in 5-m intervals along each transect, and, because we were able to create a continuous surface for these variables, we report estimated area of change (or lack thereof).

scenarios, respectively. Furthermore, in 2014/2015 and in the Intervention scenario, 9 transects had a barrier island width less than 100 m; this number increased to 86 transects in the Moderate SLC scenario and 241 transects in the No Intervention scenario. Median barrier width remained the same as observed in 2014/2015 (408 m) in the Intervention scenario due to the forced model assumption of no shoreline retreat.

We also projected declines in several elevation parameters under scenarios of increasing shoreline change rate. Although we did not allow shoreline retreat as an assumption of the Intervention scenario, we did allow the geomorphology BNs to predict biogeomorphic change (e.g., change in dune crest height) along areas of the

Table 4
Area (km²) of Fire Island Likely to Exhibit a Dynamic Response to Sea-Level Rise, by Landcover Type

Probability of dynamic response	Beach	Developed	Forest	Marsh	Subaqueous	Total
Likely ($p > 0.66$)	7.55	0.01	0.29	0.32	0.45	8.61 (43%)
As Likely As Not ($0.33 < p < 0.66$)	0.20	6.36	0.95	3.69	0.09	11.29 (57%)
Unlikely ($p < 0.33$)	0.00	0.00	0.00	0.00	0.00	0.00

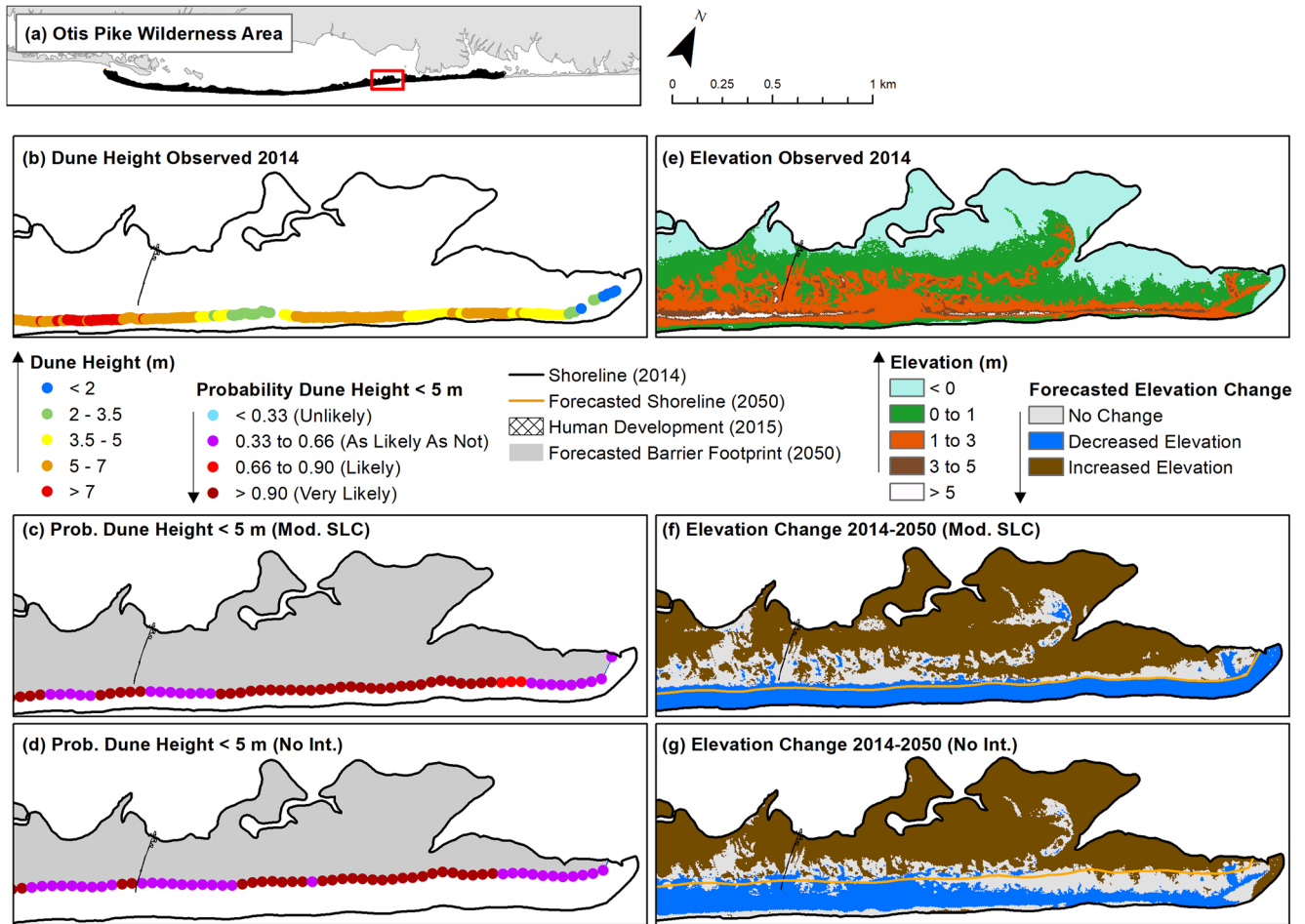


Figure 3. Forecasted geomorphic changes in the Otis Pike Wilderness Area, Fire Island: For context, we show (b) dune heights and (e) elevations observed based on 2014 lidar. For dune height forecasts, we show the probability that dune height was less than 5 m in 2050 under scenarios that assumed (c) Moderate Shoreline Change (Mod. SLC), where occasional beach nourishment would maintain the 2014 shoreline position and (d) No Intervention (No Int.), where no efforts would be made to maintain the 2014 shoreline position. For elevation, we show whether forecasted 2050 elevation increased, decreased, or did not change from 2014 conditions under the (f) Mod. SLC and (g) No Int. scenarios. This area is minimally developed and largely unmanaged. A third scenario assuming human intervention to maintain shoreline position; however, results did not differ greatly from initial conditions (b), (e).

shoreline where human development was light or not present. Under this scenario, the predicted mean transect elevation most commonly fell in bin 4 (mean transect elevation = 2–3.5 m). Mean transect elevation most commonly fell in bin 3 (1–2 m) in the Moderate SLC scenario and bin 2 (0–1 m) in the No Intervention scenario, suggesting progressively lower cross-shore profiles with increasing shoreline change and dwindling human intervention to preserve the 2014/2015 shoreline and dune structure. After using neighborhood statistics to create an elevation surface that fills in gaps/unknowns between transects, we observed that 40%–43% of the total area of Fire Island would likely decrease in elevation by 2050 compared to 2014/2015 conditions, depending on the scenario considered (Table 3; e.g., Figures 3 and 4). Finally, where predictions could be made, the dune crest elevation became lower compared to 2014/2015 conditions on 9%–15% of transects by 2050 (Table 4; e.g., Figures 3 and 4). Forecasted dune crest elevation most commonly fell in bin 4 (5–7 m) in the Intervention scenario and in bin 2 (2–3.5 m) in the Moderate SLC and No Intervention scenarios.

When we considered simultaneous changes to both barrier island width and elevation according to response regimes outlined in Passeri et al. (2020), we found that the majority (88%) of transects for which the variable's probability distribution was not uniform either maintained or increased in barrier island width and mean elevation under the Intervention scenario. Under this scenario, 2% of transects experienced a narrowing regime (where width declined as elevation was maintained or increased); 10% of transects experienced a flattening

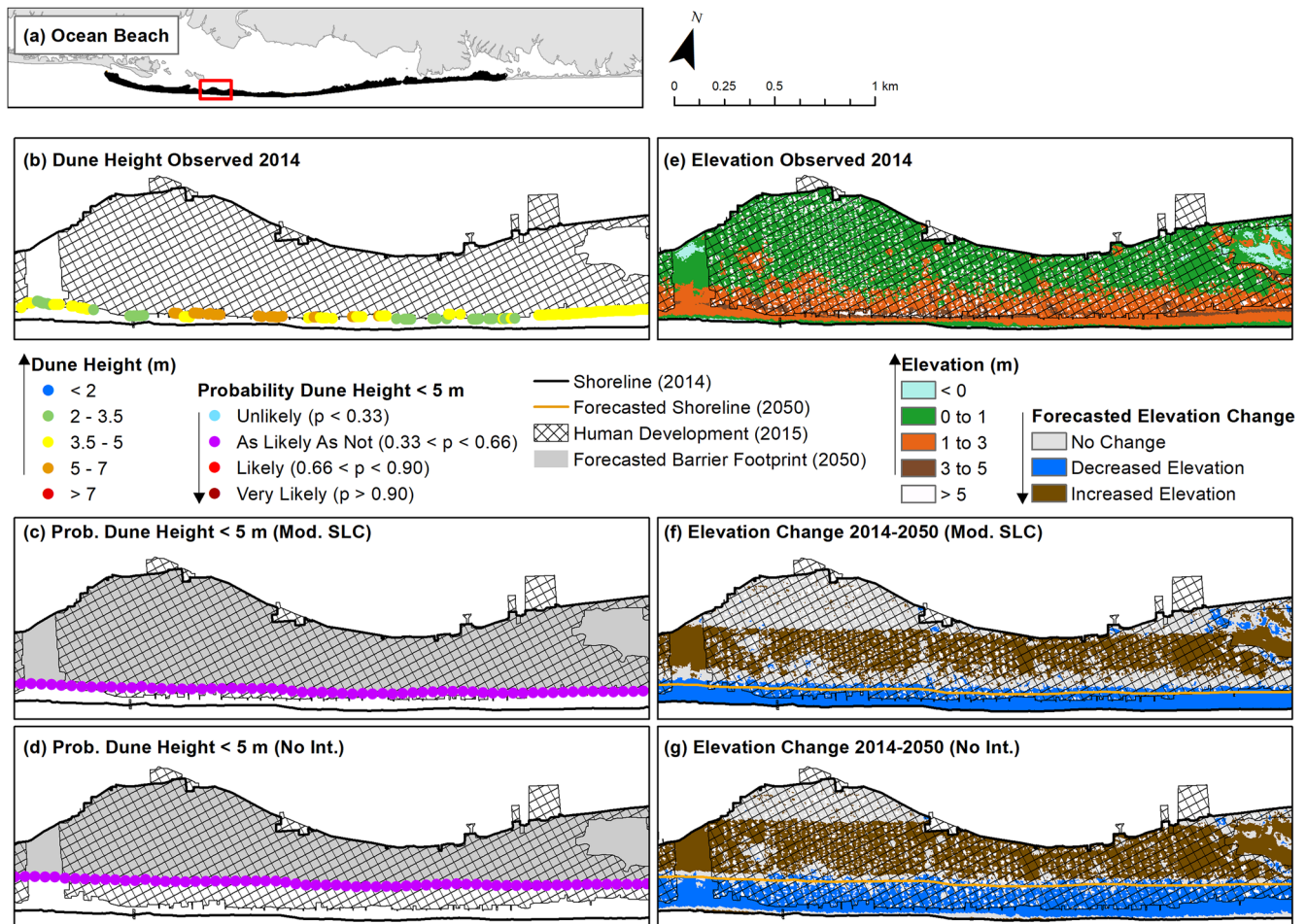


Figure 4. Forecasted geomorphic changes in the community of Ocean Beach, Fire Island: For context, we show (b) dune heights and (e) elevations observed based on 2014 lidar. For dune height forecasts, we show the probability that dune height was less than 5 m in 2050 under scenarios that assumed (c) moderate shoreline change (Mod. SLC), where occasional beach nourishment would maintain the 2014 shoreline position and (d) No Intervention (No Int.), where no efforts would be made to maintain the 2014 shoreline position. For elevation, we show whether forecasted 2050 elevation increased, decreased, or did not change from 2014 conditions under the (f) Mod. SLC and (g) No Int. scenarios. This area is densely developed and managed. A third scenario assuming human intervention to maintain shoreline position; however, results did not differ greatly from initial conditions (b), (e).

regime (where elevation declined as width was maintained or increased); and 1% of transects experienced a deflation regime (where both width and elevation declined) compared to observed 2014/2015 conditions (Table 2). Again, this change (or lack thereof) is predicated on the assumption that humans would intervene to prevent change in the shoreline and along developed portions of the primary dune line. However, as shoreline change rate increased under the Moderate SLC and No Intervention scenarios, assuming limited to no human intervention to slow erosion, a progressively larger number of transects experienced narrowing, flattening, or deflation regimes (Table 2).

Given the forecasted most likely values for dune crest elevation and beach width under each shoreline change scenario, we evaluated the likelihood that a given transect would experience an overwash event under a Category I-IV hurricane. Again, predictions could not be made for a large number of transects (Table S1 in Supporting Information), where bins for either beach width or dune crest height had a uniform probability distribution (and therefore, a most likely value could not be determined). However, of the transects where a most likely beach width and dune crest height could be determined, the percentage of transects with a ≥ 0.66 probability of experiencing overwash during a Category I hurricane increased from 4% under the Intervention scenario to 43% under the Moderate SLC scenario to 62% under the No Intervention scenario. These values increased to 12%, 74%, and 78% under each respective scenario during a Category II hurricane. Under a Category III hurricane, 79%, 100%, and

91% of transects had a ≥ 0.66 probability of experiencing overwash under the Intervention, Moderate SLC, and No Intervention scenarios, respectively. All transects had a ≥ 0.66 probability of experiencing overwash under a Category IV hurricane regardless of the shoreline change scenario (Table S1).

3.2. Barrier Island Evolution—Ecosystems

To analyze how ecosystems are likely to change with barrier island evolution, we used landcover type and geomorphic setting as proxies for ecosystem type in the Coastal Response and Geomorphology BNs, respectively. First, the Coastal Response BN predicted that 43% of Fire Island is likely to exhibit a dynamic response to SLR (Table 4). In this model, beaches were identified as the landcover type where 88% of the dynamic response occurred (Table 4), suggesting that this ecosystem would move and maintain its current form or transition to another subaerial landcover type with SLR-driven shoreline change. The remaining 57% of Fire Island was as likely as not to exhibit a dynamic response. Developed areas and marshes were largely responsible for this uncertainty, covering 56% and 33%, respectively, of the landscape that was as likely as not to exhibit a dynamic response (Table 4). No portions of the island were predicted to inundate by 2050 with high certainty (i.e., p of dynamic response ≤ 0.33).

Unlike the Coastal Response BN, the Fine-scale Geomorphology BN predicted that some subaerial geomorphic settings would transition to water (or become inundated; 1%–42% of the island), particularly in scenarios with higher rates of shoreline erosion (Table 3). We were able to further explore the nature of likely dynamic responses in the remaining regions as some geomorphic settings transitioned to other subaerial settings or remained the same. Under the Intervention scenario, with an assumption of no shoreline change through human intervention, the linked Geomorphology BNs predicted that 64% of Fire Island would maintain its current geomorphic setting. The majority of change that did occur (27% of total study area) was as a shift from one subaerial state to another (Table 3). Of the 5.6 km² that transitioned in this way, 16% and 40% occurred as washover and marsh, respectively, transitioning to barrier interior (Table S2 in Supporting Information).

As we considered higher rates of shoreline change but assumed the back-barrier shoreline would remain in its 2014/2015 position, the Fine-scale Geomorphology BN predicted that a lower percentage of Fire Island's area would remain in the same geomorphic setting. Instead, a higher percentage of the island transitioned from a subaerial geomorphic setting to water (Table 3; Figure 5). Under the Moderate SLC scenario, 44% of the island remained in the same geomorphic setting, 35% transitioned from one subaerial state to another, and 21% became inundated (Table 3). Under the No Intervention scenario, the inundation of subaerial geomorphic settings was the most common transition (42% of island), while 29% of the island experienced a transition from one subaerial geomorphic setting to another (Table 3). The remaining 29% of Fire Island maintained its 2014/2015 geomorphic setting (Table 3). For both the Moderate SLC and No Intervention scenarios, the most common transition from one subaerial setting to another occurred as barrier interior transitioned to beach and as marsh transitioned to barrier interior (Table S2). In this way, the beach geomorphic setting only declined by as much as 1.5 km² (No Intervention scenario), despite 41% of the island being inundated (Table 5; Figure 5). The linked Geomorphology BNs also predicted that many transects (12%–18%) will actually increase in beach width despite shoreline erosion in these scenarios (Table 3), further supporting the idea that beaches will respond dynamically to SLR and shift landward with the new shoreline position.

The linked Geomorphology BNs predicted that the barrier interior geomorphic setting will either gain (Intervention and Moderate SLC scenarios) or only lose a small amount of area (No Intervention scenario) by 2050 compared to 2014/2015 conditions (Table 5; e.g., Figure 5). Where barrier interior was lost, it most often transitioned to beach, dune complex, or, to a lesser extent, marsh (Table S2).

In contrast to beaches, marsh geomorphic settings were predicted to suffer the largest losses according to the linked Geomorphology BNs, although this result is at least in part driven by the model assumption that the ocean shoreline would retreat while the back-barrier shoreline would remain in its 2014/2015 position. Marshes covered 3.5 km² based on 2015 aerial imagery but were reduced to 0.8 and 0.3 km² in the Moderate SLC and No Intervention scenarios, respectively (Table 5; Figure 5). In both scenarios, the majority of marshes were converted to barrier interior (Table S2).

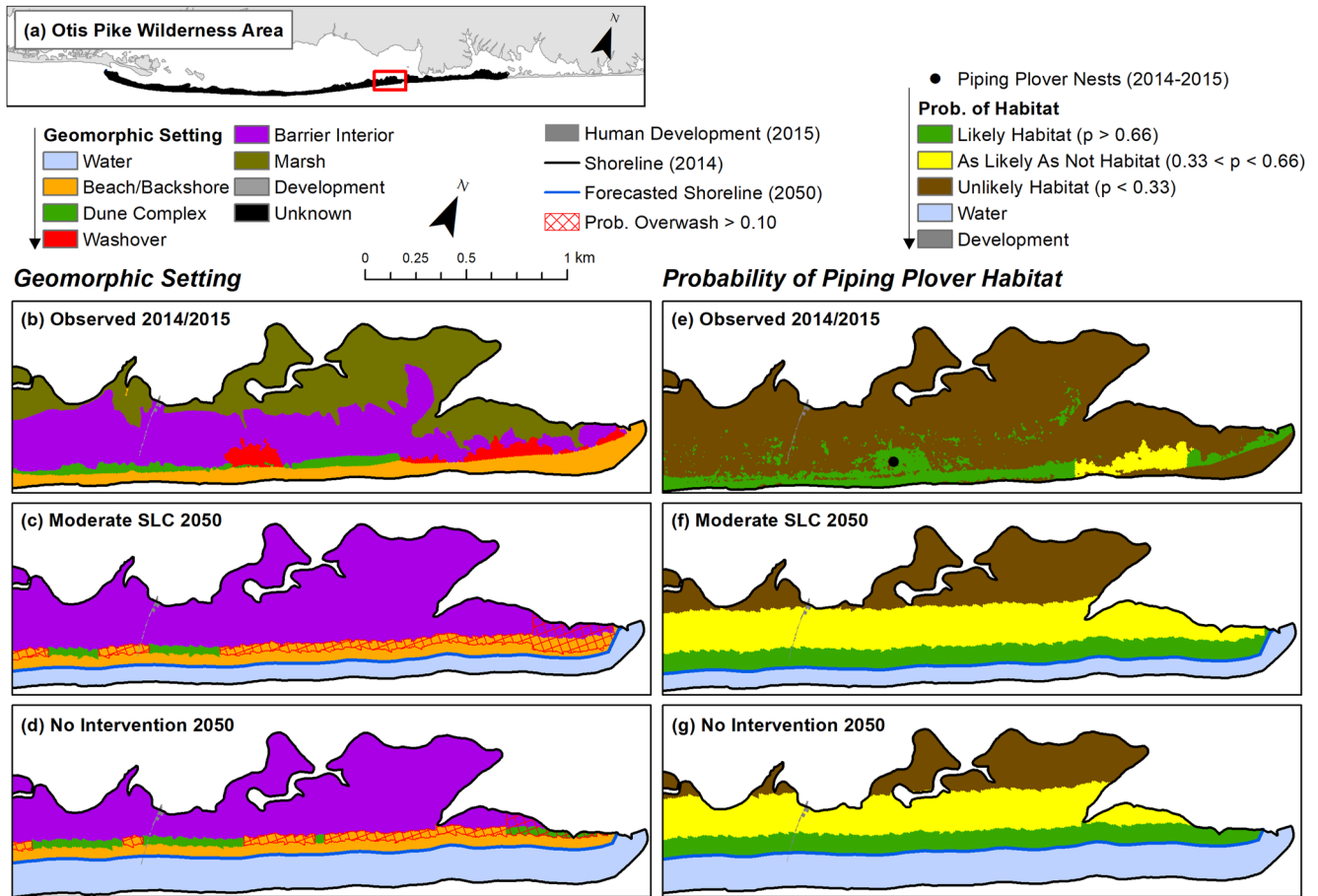


Figure 5. Forecasted changes geomorphic setting and piping plover habitat availability in the Otis Pike Wilderness Area, Fire Island: For context, we show (b) geomorphic settings and (e) piping plover habitat observed based on 2014 lidar and 2015 orthoimagery. Forecasted geomorphic settings in 2050 were made under scenarios that assumed (c) moderate shoreline change (Moderate SLC), where occasional beach nourishment would maintain the 2014 shoreline position and (d) No Intervention, where no efforts would be made to maintain the 2014 shoreline position. This area is minimally developed and largely unmanaged. A third scenario assuming human intervention to maintain shoreline position; however, results did not differ greatly from initial conditions (b), (e).

Finally, dune complexes and washovers—which cover only a small extent of Fire Island compared to other geomorphic settings according to 2014/2015 imagery—were predicted to decline with increasing rates of shoreline change (Table 5; Figure 5). When not inundated by SLR, dune complexes tended to transition to beach or barrier interior as the shoreline position shifted, while washovers tended to transition to beach, dune complexes, or barrier interior (Table S2). However, the loss of these geomorphic settings is likely due to the probabilistic nature of the BNs and not due to geomorphological processes; settings that covered a small area in the training dataset were rarely predicted to be the most likely setting present in forecasted outputs.

3.3. Changes to Human and Piping Plover Habitat

The changing shoreline position and biogeomorphological conditions also impacted ‘habitats’ used by humans and piping plovers. In the Moderate SLC scenario, partial extents (0.2 km² total) of housing communities and recreational infrastructure (e.g., boardwalks) were predicted to be seaward of the 2050 shoreline position. The areal extents that were seaward of the 2050 shoreline increased to 1.4 km² in the No Intervention scenario (Table S2; Figure 4).

We found that 31 of 53 piping plover nests present in 2014 or 2015 were located in areas that the Coastal Response BN predicted would respond dynamically to SLR. The remaining 22 nests were located in areas that were as likely as not to respond dynamically. An additional 3 nests were located outside of the model’s predictive

Table 5
Forecasted Area (km²) and Percentage Total Area for Geomorphic Setting^a and Piping Plover Habitat^b on Fire Island in 2050

Characteristic	Area (km ² ; percentage of study area) by scenario			
	Observed 2014 - 2015	Intervention	Moderate SLC	No Intervention
<i>Geomorphic Setting</i>				
Seaward of Shoreline/Water	0 (0%)	0.2 (1%)	4.3 (21%)	8.5 (41%)
Beach/Backshore	3.5 (17%)	2.3 (11%)	2.6 (12%)	2.0 (10%)
Dune Complex	1.5 (7%)	1.4 (7%)	0.9 (5%)	0.8 (4%)
Washover	1.2 (6%)	0.0 (0%)	0.0 (0%)	0.0 (0%)
Barrier Interior	6.4 (31%)	8.9 (43%)	7.6 (37%)	5.7 (28%)
Marsh	3.5 (17%)	1.6 (8%)	0.8 (4%)	0.3 (2%)
Development	4.5 (22%)	4.5 (22%)	4.3 (21%)	3.1 (15%)
Unknown	0.0 (0%)	1.7 (8%)	0.0 (0%)	0.0 (0%)
<i>Piping Plover Habitat</i>				
Likely Habitat	5.1 (25%)	4.3 (21%)	3.6 (17%)	2.8 (14%)
As Likely As Not Habitat	0.7 (3.6%)	6.4 (31%)	4.9 (24%)	4.0 (19%)
Unlikely Habitat	10.3 (50%)	5.2 (25%)	3.5 (17%)	2.0 (10%)
Water or Development	4.5 (22%)	4.7 (23%)	8.6 (42%)	11.6 (57%)

Notes. Forecasts were made in scenarios that assumed (i) human intervention to maintain the current shoreline position (e.g., through beach nourishment; 'Intervention'); (ii) moderate shoreline change resulting from some human intervention to stabilize the shoreline ('Moderate SLC'); and (iii) high rates of shoreline change resulting from a lack of human intervention to stabilize the shoreline ('No Intervention'). ^aThe forecasted value of a given 5 × 5 m landscape cell was determined according to the Fine-scale Geomorphology Bayesian Network (BN). For each variable, we selected the value that had the highest probability of occurring according to the BN. ^bWe identified a given 5 × 5 m landscape cell as 'likely habitat' if the Piping Plover Habitat BN indicated a probability of containing habitat ≥0.66 given underlying landscape characteristics (e.g., geomorphic setting, elevation). 'As likely as not habitat' was associated with a probability between 0.33 and 0.66, and 'unlikely habitat' was associated with a probability ≤0.33.

coverage area. The linked Geomorphology BNs predicted that areas that had a high likelihood of supporting piping plover habitat—flat, minimally vegetated, sandy beach, dune, and washover settings—would shift with the shoreline under the three scenarios of shoreline change (e.g., Figure 5). However, the BNs also predicted a reduction in total piping plover habitat areas from the 5.1 km² observed in 2014/2015 to 4.3 km², 3.6 km², and 2.8 km² by 2050 under the Intervention, Moderate SLC, and No Intervention scenarios, respectively (Table 5; Figure 5). This loss may be in part due to loss of certainty in beach morphological conditions, which we explore further in Section 4.

4. Discussion and Conclusions

4.1. Uncertainty in Biogeomorphological Forecasts

Making high-confidence predictions about climate change and SLR is difficult, as these processes are often characterized by 'deep uncertainty' (Bell et al., 2014). The expected magnitude of SLR into the future is unclear and dependent on future emission levels and Antarctic and Greenland ice sheet contributions (Bell et al., 2014). There is also substantial uncertainty in how geologic landforms, ecosystems, and humans will respond to rising sea levels, which will each contribute to the manner in which SLR will ultimately transform coastlines (Bell et al., 2014; Moser, 2005). Finally, the inherent structures and assumptions of SLR models add uncertainty to predictions (Carson et al., 2019). However, the potential economic, social, and ecological consequences may be high without active SLR planning (Hallegate et al., 2013; Hauer et al., 2016; Hinkel et al., 2014; Leatherman, 2001). Interdisciplinary models—including scenario-based exercises—and decision frameworks that

explicitly consider uncertainty are helpful for pre-emptively responding to changing coastal conditions (Haasnoot et al., 2013, 2020; Moss et al., 2010).

Uncertainty is intrinsically quantified by our models. Knowing where uncertainty is high—particularly in predictions of mean barrier island transect elevation, barrier island and beach width, elevation, and dune height—is an important finding in and of itself in this study. BNs employed here were parameterized with previously observed, historical barrier island and ecosystem dynamics on Fire Island. Uncertainty occurred here through two mechanisms. First, the Fire Island coastline has yet to experience the highest rates of SLR or associated biogeomorphological conditions that are expected in the (Hapke et al., 2010; Sweet et al., 2017) future, and combinations of higher shoreline change rates and initial biogeomorphological conditions are not currently present in the training data for the Coarse-scale Geomorphology BN. Incorporating additional training data sampled from other barrier islands in future iterations of this work may reduce both error and uncertainty in BN predictions by providing a broader range of conditions, including island evolution for locations that have experienced higher rates of shoreline change compared to Fire Island. Second, this region has experienced a long history of shoreline stabilization, including shoreline armoring and beach nourishment (Rice, 2015), that likely mask ‘true’ rates of shoreline change (Armstrong & Lazarus, 2019) in the training data. Therefore, we expect that Fire Island shorelines and geomorphology will evolve in ways not previously observed at this location as SLR rates increase and if human intervention relaxes. A shift from a more likely range to a more uncertain range in our outcomes implies that we are no longer as confident that Fire Island will evolve in response to SLR as it has in the past. As SLR drives non-equilibrium behaviors in barrier island biogeomorphic evolution (Hughes et al., 2013), ecological surprises and no-analog futures are expected (Williams & Jackson, 2007).

4.2. Predicted Biogeomorphological Change on Fire Island

Despite predicting high uncertainty in some biogeomorphic variables, we were able to observe several likely trends for others with increasing shoreline change. At present, Fire Island is a barrier island characterized by high positive relief and resistance to disturbance (Vincent & Moore, 2015; Zinnert et al., 2017), owing in part to a long history of beach nourishment and other activities to stabilize the island's ocean and back-barrier shoreline position. Higher elevation barrier islands with well-developed dune structures, as Fire Island has historically been, are more resistant to storm effects, migrate landward more slowly, and support late-successional ecosystems like maritime forests (Vincent & Moore, 2015; Zinnert et al., 2017). High-elevation islands with stable dunes also help to preserve homes and infrastructure landward of dune features in the short-term but potentially make the system vulnerable to longer-term impacts by limiting overwash fluxes as well as the gradual lateral translation of these environments necessary for their adaptation and landward migration (Lorenzo-Trueba & Ashton, 2014). However, our model simulations show that the island may begin to transition to a relatively low elevation, disturbance-reinforcing landscape as rates of SLR increase and efforts to stabilize the shorelines diminish (Vincent & Moore, 2015; Zinnert et al., 2017). Along many transects under the Moderate SLC and No Intervention scenarios, Fire Island became increasingly flatter, narrower, and more prone to overwash. Low elevation islands with minimal dune structures experience repetitive overwash events that hinder growth of dune-building plants and reduce the likelihood that dunes will form. Such islands become perpetually ‘trapped’ in a low-elevation state where early successional ecosystems are prevalent (Lorenzo-Trueba & Ashton, 2014; Zinnert et al., 2017). These low-profile islands often lack stability required for supporting human development but provide prime foraging and nesting habitat for many coastal species, including shorebirds (U.S. Fish and Wildlife Service, 2020).

Similar transitions from high-to low-elevation biogeomorphological states have been demonstrated for barrier islands both in other models and in real-world examples. For instance, model simulations have shown that barrier islands with closed sediment budgets will experience shoreface flattening and island narrowing as sea levels rise (Lorenzo-Trueba & Ashton, 2014; Passeri et al., 2020). Declining sediment availability further accelerates this process and may drive equivalent state changes in neighboring barrier islands (Ciarletta et al., 2021). Historical barrier island state changes have been documented for Cedar, Hog, and Parramore islands off the coast of Virginia, which transitioned to low elevation, erosional states during periods of higher relative SLR punctuated by storms (Dueser et al., 1976; Raff et al., 2018; Shawler et al., 2019). This led to a drastic change in long-established ecological communities and a slow retreat of permanent human residents from Hog Island in the 1930s and Cedar Island in the late 1990s (Dueser et al., 1976; Horton, 1998), and both islands remain uninhabited

today. Low elevation islands can transition to high elevation islands and vice versa depending on storm and wave regimes; however, feedbacks tend to maintain these landforms in one state or the other (Vincent & Moore, 2015). Transitions in barrier island state may be accelerated as storms are expected to amplify SLR effects in non-linear ways (Buchanan et al., 2017; Wahl, 2017). Thus, our model of biogeomorphological change as well as historical accounts of change on similar barrier islands indicate that SLR could drive major changes to the morphological and ecological state of Fire Island, potentially leading to drastic landuse changes.

Island narrowing predicted by the geomorphology BNs was in part due to assumptions we made in the application of the model; we assumed that, as the ocean shoreline retreated with SLR, the back-barrier shoreline would be held in its 2014 position. Along the majority of Fire Island (66% of the back-barrier shoreline), a fixed back-barrier shoreline is consistent with existing vegetation, human development, seawalls, and bulkheads that would prevent natural overwash processes that would otherwise extend the back-barrier and allow the island to keep pace with SLR. According to interpretations of 2015 aerial imagery (Zeigler, Sturdivant et al., 2019), 16 km (21%) of the back-barrier shoreline was stabilized in some manner, typically through seawalls, rip-rap, and bulkheads. An additional 3 km (4%) and 31 km (41%) of the back-barrier shoreline was separated from the ocean by dense housing development or shrub/forest vegetation, respectively. Field studies have shown that upland areas with woody vegetation—like those found extensively across Fire Island (Sturdivant et al., 2019)—can act much like development in blocking overwash processes (Zinnert et al., 2019). Hardened anthropogenic structures and dense woody vegetation could block overwash from reaching back-barrier flats and prevent the island from naturally building elevation, extending marsh platforms, and migrating into Great South Bay. Consequently, some portions of Fire Island tend to evolve differently than adjacent unmanaged barrier island settings that are allowed to erode, migrate landward, and evolve naturally (Lentz et al., 2013). In addition, a comparison of Fire Island's back-barrier shoreline in 2010, 2012 (immediately after Hurricane Sandy), and 2014 indicate very little movement in that shoreline's position, even after a major storm event (Sturdivant et al., 2019; Zeigler, Gutierrez, et al., 2019). A previous study has also shown evidence of erosion along the back-barrier shoreline of Fire Island, particularly around bulkheads and marinas (Nordstrom & Jackson, 2005). Therefore, our assumption of a fixed back-barrier shoreline on Fire Island and the resulting island narrowing that may occur as the ocean shoreline erodes is not unrealistic for the time scale considered in this study.

Island cross-sections under narrowing or flattening regimes highlight areas that may be prone to width or height drowning, respectively, where sediment transport is insufficient to maintain an island's geometry during landward migration in response to SLR (Lorenzo-Trueba & Ashton, 2014; Passeri et al., 2020). The 52% and 47% of transects in the Moderate SLC and No Intervention scenarios, respectively, that reflect narrowing or flattening regimes are unlikely to keep pace with SLR over the long-term (Lorenzo-Trueba & Ashton, 2014; Passeri et al., 2020). In addition, another 7% and 16% of transects under the Moderate SLC and No Intervention scenarios exhibit deflation regime trends. These sections of Fire Island are also unlikely to keep pace with SLR over the long-term and may be likely locations for storm breaching (Passeri et al., 2020).

Our results also show potential ecosystem state changes with shoreline change as the geomorphological landscape shifts. Beach ecosystems were the most resilient to SLR in both the Coastal Response BN and linked geomorphology BNs. In the Coastal Response BN, beaches accounted for almost all of the landscape predicted to respond dynamically to SLR. Similarly, according to the geomorphology BNs, beaches lost only 1.5 km² even under the high erosion rates of the No Intervention scenario as other geomorphic settings (e.g., barrier interior) were predicted to shift from their original state to beach with shoreline change. Beaches are well-suited for dynamic changes with SLR; these ecosystems are comprised of finer substrates that move in response to wind and wave action (Carter, 1988; Davis jr, 1994; Leatherman, 1979; Oertel, 1985), and common types of beach vegetation (e.g., *Ammophila breviligulata*) adapted to periodic burial can survive and stabilize beach and dune landscapes (Zinnert et al. [2017] and references therein). This dynamic response of beach ecosystems to SLR, however, is predicated on the ability of these ecosystems to migrate. Human development and stabilization structures (e.g., seawalls, engineered dunes) can block overwash processes and beach migration, causing coastal squeeze and the ultimate loss of this ecosystem (Magliocca et al., 2011; Rogers et al., 2015).

In contrast to beaches, coastal marsh may likely be lost (according to the linked geomorphology BNs) or have a largely uncertain fate (according to the Coastal Response BN). In the linked geomorphology BNs, marshes were predicted to lose as much as 3.2 km² (No Intervention scenario) of the 3.5 km² present in 2015 aerial imagery. This loss was in part due to our assumption of no back-barrier shoreline migration. Others have shown

that healthy marshes are able to keep pace with low to moderate rates of SLR (Kirwan & Megonigal, 2013; Kirwan & Murray, 2007). These ecosystems increase biomass production in response to increased water depths, which allows for increased deposition and stabilization of the marsh platform in step with rising water levels. Storm overwash can also move sediments from beach and dune systems to marshes in the back-barrier, providing additional elevation and facilitating marsh migration with SLR (Kirwan & Megonigal, 2013; Kirwan & Murray, 2007). Therefore, our model scenarios may be overestimating the loss of marshes on Fire Island in locations where a lack of back-barrier bulkheads, housing communities, and dense woody vegetation would allow overwash fluxes into the barrier interior. However, marshes are already rapidly declining throughout the U.S. Atlantic coast. Studies have revealed the conversion of high marsh vegetation communities to low-elevation, flood-tolerant species (Field et al., 2016; Ganju et al., 2020; Kirwan & Murray, 2007; Morris & Renken, 2019; Raposa et al., 2017). Such altered communities are less resilient and are more likely to be converted to open water (Kirwan & Megonigal, 2013; Kirwan & Murray, 2007; Raposa et al., 2017), and some studies suggest that marsh surface elevation in Great South Bay (where Fire Island is located) will not be able to keep pace with SLR (Ganju et al., 2020; Morris & Renken, 2019). The ability of marshes to keep pace with SLR will depend on their ability to migrate, and prevalent human development and woody vegetation on Fire Island may prevent this through coastal squeeze (Pontee, 2013; Zinnert et al., 2019). Some observational studies have also noted the loss of marshes to colonization by upland woody vegetation along the Virginia coast (Zinnert et al., 2019)—a dynamic observed in our model predictions given that as much as 65% of marsh converted to the barrier interior geomorphic setting in the No Intervention scenario. Ultimately, the response of marsh ecosystems is also highly dependent on sediment availability and other localized characteristics (van Belzen et al., 2017; Kirwan & Megonigal, 2013; Kirwan & Murray, 2007; Philips, 2017). Such context-specific information would need to be included with an explicit consideration of marsh evolution and back-barrier shoreline migration to generate high-confidence forecasts of marsh persistence. Without this information, the fate of marshes and their ability to respond dynamically to SLR leads to high uncertainty, as captured in the Coastal Response BN.

4.3. Implications of Change for People and Piping Plovers

The biogeomorphological changes predicted by our suite of models have important implications for both people and endemic species like the piping plover. With predicted narrowing under the Moderate SLC and No Intervention scenarios, the subaerial footprint of Fire Island becomes smaller—leading to less overall area for both people and other species. If the rates of shoreline retreat modeled in this study are realized at Fire Island, 0.2–1.4 km² of the existing footprint of housing communities and recreational infrastructure would be seaward of the mean high water shoreline by 2050. As beaches replace more stable dune and barrier interior geomorphic settings and as the island becomes lower and more prone to overwash, substantial increases in the frequency and extent of tidal and storm surge flooding would also be expected—particularly for properties now adjacent to a shoreline that shifted by as much as 175 m in 2050 predictions. Furthermore, several studies have shown that buildings and coastal engineering designed to slow shoreline erosion and storm flooding may actually exacerbate problems associated with SLR (Magliocca et al., 2011; Nordstrom & McCluskey, 1985; Rogers et al., 2015). The primary mechanism by which barrier islands keep pace with SLR is through overwash, inlet formation, and island roll-over (i.e., where sand is moved by waves from the ocean shoreline into the island interior and back-barrier). Structures like artificial dunes, seawalls, and buildings block overwash deposition except during relatively rare, very high intensity storms (Nordstrom & McCluskey, 1985; Rogers et al., 2015). As a result, areas landward of artificial dunes and other structures remain at the same elevation and the back-barrier shoreline remains in a fixed position as the ocean shoreline retreats and sea levels rise. Such engineered or developed islands tend to narrow more rapidly and experience more catastrophic flooding and overwash than islands allowed to evolve naturally (Magliocca et al., 2011). Therefore, further engineering Fire Island with artificial dunes, rip-rap, and other hard stabilization structures may protect current residential, commercial, and recreational investments over the short-term but at the cost of long-term barrier island resilience (Magliocca et al., 2011).

As Fire Island's morphology shifts to a lower, more overwash-prone state, piping plovers and other endemic beach species may benefit from SLR-driven changes, as in Seavey et al. (2011). Although the amount of habitat for piping plovers is also expected to decline with the decrease in the subaerial footprint of Fire Island, some of this loss may be due to propagated uncertainty in model results as opposed to actual loss of future habitat. Gutierrez et al. (in press) found that, with increased model complexity in the linking of BNs, predictions for

biogeomorphological characteristics became more uncertain (which was also found with increasing shoreline change). As the nature of these underlying characteristics became more uncertain, the Piping Plover Habitat BN exhibited more uncertainty in predictions of habitat availability, which appears as habitat loss as landcover predicted to be habitat with high certainty (i.e., ≥ 0.66 probability) becomes more uncertain in 2050 predictions. Scenario-based numerical models of barrier island evolution (e.g., Passeri et al., 2020) could reduce the amount of uncertainty propagated through estimates of piping plover habitat availability; however, such models are data- and computationally intensive.

Furthermore, other biogeomorphological features predicted under the Moderate SLC and No Intervention scenarios suggest that habitat could actually be improved with coastal storms. Nesting piping plovers prefer low-elevation sandy habitats in beach/backshore areas, natural dune complexes, and washover features (Zeigler et al., 2021). Because beach ecosystems are able to respond dynamically to SLR and because overwash likelihood increases as the island get flatter, piping plover habitat is not expected to be lost as rapidly as one might expect given the rate of shoreline migration. That said, management of the shoreline-adjacent built environment (e.g., sea walls, engineered dunes) will determine the extent to which natural overwash processes occur and that beach ecosystems and associated piping plover habitats can migrate with rising sea levels. This species and other shorebirds quickly colonize storm-created habitats (Zeigler, Gutierrez, et al., 2019), often at higher population densities (Cohen et al., 2009) and frequently leading to irruptions in population abundance and productivity important for the long-term viability of the species (Robinson et al., 2019). If built features block natural coastal processes (e.g., Magliocca et al., 2011; Rogers et al., 2015), the coastal squeeze will occur, and we would expect the loss of beach ecosystems and habitats as the shoreline migrates landward with SLR (Defeo et al., 2009). In addition, a smaller Fire Island subaerial footprint with SLR means that humans and endemic wildlife will co-exist in a smaller area, increasing the potential for human wildlife conflicts. Because disturbance-related stress can harm individual shorebirds and have population-level consequences (Gibson et al., 2018), efforts to minimize human disturbance in high quality beach habitats are important on a shrinking barrier island if this environment is expected to contribute to population recovery. Maintaining beach habitats for piping plovers and other shorebirds on Fire Island into the future is especially important in this region, where few undeveloped barrier islands remain for breeding and migration in the federally designated New York–New Jersey recovery unit (U.S. Fish and Wildlife Service, 2020).

Finally, although the No Intervention scenario and its predicted biogeomorphological evolution were intended to serve as the worst case scenario in terms of the highest levels of shoreline erosion, current trends suggest that this scenario may also be the most likely. Trends in global mean SLR and emission rates have prompted scientists to increase extreme upper bounds of SLR to 2.5 m above 1991–2009 levels (Sweet et al., 2017), and rates along the U.S.'s northeastern Atlantic coast are predicted to be higher than the global mean (Goddard et al., 2015). Higher rates of SLR will drive higher rates of shoreline erosion. In the No Intervention scenario, we assumed a mean rate of shoreline erosion of -4.71 m/year; higher rates of relative SLR and shoreline change have already been observed off the coast of the nearby Delmarva Peninsula as well as the Louisiana coast (Hapke et al., 2010; Himmelstoss et al., 2010). Furthermore, sand is becoming one of the most in-demand, expensive, and limited resources in the world (Peduzzi, 2014). Mitigation efforts that rely on adding sand to a sediment-starved system—through, for example, beach nourishment—may become too expensive for communities addressing climate change effects (Keeler et al., 2018; McNamara et al., 2015). Paired economic-geomorphological models suggest that as the cost of coastal engineering becomes prohibitive and as government subsidies for sand nourishment are removed, property values will decline (Keeler et al., 2018; McNamara et al., 2015).

5. Summary

In summary, our model simulations suggest that Fire Island will become increasingly flatter, narrower, and more overwash-prone with increasing rates of shoreline change. Common engineering strategies to prevent overwash and shoreline erosion—including artificial dunes and beach nourishment—may provide short-term protection for residential, commercial, and recreational infrastructure; however, these strategies may become cost-prohibitive and hinder the long-term resilience of Fire Island to SLR. Instead, Fire Island may offer a conservation opportunity for piping plovers and other endemic coastal species that rely on early successional beach environments, should natural overwash processes be encouraged.

Data Availability Statement

All supporting data can be found in previous publications (Lentz et al., 2015b; Sturdivant et al., 2016, 2019).

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