OCS Study
BOEM 2024-033

Productivity and Ecology of Sand Shoals System Modeling

U.S. Department of the Interior
Bureau of Ocean Energy Management
Sterling, VA

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ABOUT THE COVER

A sand lance in sand. Courtesy of NOAA.

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List of Abbreviations and Acronyms

BOEM	Bureau of Ocean Energy Management
BU	Boston University
CHANS	coupled human and natural systems
DPSIR	Driver-Pressure-State-Impact-Response
EBM	Ecosystem-Based Management
GIS	geographic information system
IPCC	Intergovernmental Panel on Climate Change
MARCO	Mid-Atlantic Regional Council on the Ocean
MCY	million cubic yards
MIDAS	Marine Integrated Decision Analysis System
MIMES	Multiscale Integrated Models of Ecosystem Services
MMIS	Marine Minerals Information Systems
MMP	Marine Minerals Program
NJ-MIMES	New Jersey MIMES Model
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
RCP	Representative Concentration Pathways
SBT	Sea Bottom Temperature
SB-MIMES	Stellwagen Bank National Marine Sanctuary MIMES Model
SBNMS	Stellwagen Bank National Marine Sanctuary
TNC	The Nature Conservancy
UConn	University of Connecticut
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WHOI	Woods Hole Oceanographic Institute

1 Project Summary

This study on the ecology, management, and productivity of sand shoals was conducted with support from BOEM's Environmental Studies Program. Offshore sand habitats supply a range of ecosystem goods and services to people. Anthropogenic disturbance (i.e., sand dredging) can impact benthic communities in ways that could have indirect effects on commercial fisheries. One goal of this work was to understand how different dredging scenarios can directly impact marine life, which indirectly impacts fisheries. Although sand dredging and commercial fishing may seem unrelated, the continental shelf sands suitable for beach renourishment are also the habitat for a myriad of organisms essential to fisheries production and biodiversity maintenance. Sand lance fishes (genus *Ammodytes*) were chosen as the focus of this study because they are the main prey item for several commercially fished species (as well as protected marine wildlife) in the northeastern and Mid-Atlantic US Outer Continental Shelf (OCS). Sand lance are also highly dependent on sand for habitat and protection during all life stages and are therefore particularly vulnerable to impacts from dredging.

Sand dredging has become an increasingly important activity for managing coastal erosion, which occurs naturally (e.g., natural sediment transport) but can be accelerated by climate change (Armstrong and Lazarus 2019; Johnson et al. 2015). Here, we report on a systems-level dynamic model, the Multiscale Integrated Models of Ecosystem Services (MIMES), which was developed to explore different scenarios to better understand how the timing and location of sand dredging can affect benthic communities and examine impacts to commercial fisheries through the lens of sand lance ecology. MIMES was developed in close coordination with researchers at the Stellwagen Bank National Marine Sanctuary (SBNMS); data collection in the sanctuary provided new empirical data that was invaluable for understanding this system.

The model and its visualization interface provide decision support to help understand how the timing and location of sand dredging can affect the benthic community in different ways.

Our project goals include the following:

- Integrate empirical results from fieldwork conducted in concert with study partners (i.e., Boston University (BU), SBNMS, University of Connecticut (UConn), and Woods Hole Oceanographic Institute)
- Develop a decision support tool to model marine and coastal system dynamics; our integrated dynamic MIMES systems model aims to identify the times and locations of sand dredging with minimal impact on sand lance, the sand shoal habitat, and its ecosystem
- Reveal likely effects on commercial fisheries based on sand lance biomass dynamics and predator-prey relationships
- Design trade-off scenarios to minimize the impacts to commercial fishing and optimize sand dredging for beach renourishment
- Visualize decision trade-offs to relate our insights and findings to best guide sand dredging strategies that are minimally damaging to offshore benthic communities

As global climate change increasingly impacts the marine environment and its resources, we need methods to help us adapt to and mitigate its effects. The creation of a systems model can help us understand the combined impacts of climate change and how best to manage different scenarios.

2 Background—Sand Habitats

Offshore sand habitats supply a range of ecosystem goods and services. Sand dredging activities can directly impact fisheries by physically altering habitat and indirectly by impacting areas where fishermen fish, resulting in reduced fishery productivity (Auster and Langton 1999; Auster et al. 2011; Lindholm et al. 2001; Long et al. 2021; Pitcher et al. 2022; Watling and Norse 1998). Sand habitats support unique communities of marine organisms that include threatened and endangered species and many commercially important finfishes such as flatfishes (i.e., yellowtail flounder). Many marine species rely on demersal organisms for food, including those that are highly dependent on sand habitats such as sand lance and sand dollars. Sand communities are also influenced by benthic landforms, current-sculpted sand waves, and biogenic structures created by organisms that benefit from sand wave microhabitats (Lindholm et al. 2004).

Although some sand habitats are highly resilient to physical disturbance (Dernie et al. 2003), anthropogenic disturbance to these systems is not necessarily benign (Auster et al. 2013). Sand habitats are dynamic, and therefore species that dwell in coarse sands must be adaptable to a continually changing environment. The physical characteristics and biological importance of sand—as well as its recent history—vary with the kinds of organisms that occupy it. Disturbance is variable based on local conditions and the size of organisms (Mercaldo-Allen and Goldberg 2011). Sand habitat varies along a spectrum, providing structure that allows for high mobility to very low mobility for benthic organisms, the latter caused in part by structure-building invertebrates that live semi-infaunal and often accumulate in the troughs of sand waves (Lindholm et al. 2004).

Although benthic communities of coarse sands may, in general, be more adaptable to physical disturbance than muddy sand, mud, or rocky environments, they are not invulnerable to disturbance. Some sand communities may recover (i.e., rebuilding species composition, biomass, the assemblage of tube-constructors and epifaunal structure-builders) more quickly on average than those of muddy or rocky environments (Kaiser et al. 2006; Lindholm et al. 2004). Still, for low mobility sands where the benthic community has matured and is structured by living organisms like sponges, and activities such as invertebrate tube building and recovery can take much longer.

Compared to mud, muddy sand, or hard bottoms, offshore coarse and mobile sand communities are more subject to highly stochastic fluctuation (Lindholm et al. 2004). In ecology, stochasticity refers to unpredictable events affecting population and community dynamics (e.g., climate change results in stochastic environmental variability). Therefore, in some areas, it may appear that impacts of sand dredging could be no different than a bad winter storm. Shallow, exposed sand assemblages routinely exposed to intense winter storms are adapted to them (Hawkins et al. 2019; Woodin et al. 2019). Still, even by this logic, dredging should only take place when the benthic biomass is at a minimum and natural disturbance (e.g., from storms) is at a maximum (Transportation Research Board 2002; Murawski et al. 2000; Reine et al. 1998). If dredge impacts are similar to winter storms, dredging during the winter may have similar recovery patterns as natural storms, whereas summer dredging does not have an equivalent natural perturbation (Grothues et al. 2021). In addition, from an ecological or fisheries perspective, some of the most critical sand dwellers exhibit brief warm-season life histories, migrating south and/or seaward in the winter—a common pattern for birds, marine mammals, sea turtles, and many fishes. The implication is that the system could be quite vulnerable if sand dredging were slated for spring through fall (when diversity is higher) or conducted widely on mature sand bottoms.

One of the sand habitat's most important inhabitants is a group of fish species in the family *Ammodytidae*, commonly known as the sand lance. These are bottom-dwelling fishes that typically rise into the water column during the day to feed on large, nutrient-rich pelagic copepods, *Calanus finmarchicus.* Sand lance are a common prey item for many organisms in the region including the critically endangered North

Atlantic right whale. Sand lance are key species for understanding the ecology of the Northwestern Atlantic continental shelf and associated ecological communities. They are the main prey species for a wide array of commercially and recreationally important fishes, seabirds, and marine mammals. The genus *Ammodytes* is therefore ecologically and economically critical to the coast of the northeastern and Mid-Atlantic US.

The two species of sand lance that are important foragers along the northeastern coast of the US are the northern sand lance (*Ammodytes dubius*) and the American sand lance (*Ammodytes americanus*) (Page et al., 2013). The habitat of *A. dubius* extends from Canada to North Carolina and overlaps broadly with offshore deposits of sand suitable for dredging (e.g., correct grain size, type of sand, and depth). The habitat of *A. americanus* is similarly extensive, ranging from Canada to Delaware, but is mainly restricted to coastal areas (i.e., beaches and the nearest offshore sandbanks).

Like other small pelagic species at the base of the marine food web, sand lance can undergo significant and chaotic fluctuations in population and spatial distribution over time. In the North Sea, where closely related species occur, a sandbank may host dense populations for several years, and then almost none, while neighboring sandbanks may be fluctuating in sand lance abundance as well, but out of phase (van Deurs et al. 2012). This observation suggests that 1) sand lance often do not saturate available habitat, and 2) their distribution within appropriate habitat varies irregularly. In the Gulf of Maine, sand lance abundance appears to cycle up and down approximately every 7 years in what may be a semi-regular manner (Nelson and Ross 1991).

Our recent field and laboratory studies in collaboration with the SBNMS (Staudinger et al. 2020; Suca et al. 2021) have revealed much about sand lance ecology. Although the American sand lance occupies the impact zone for beach renourishment, its habitat preferences render it most relevant to sand dredging in waters under state jurisdiction. With respect to offshore sand dredging, findings suggest there is more potential to impact the habitat of the northern sand lance compared to the American sand lance. This study, therefore, focused on the northern sand lance, *A. dubius*.

We have incorporated new research into the work reported here, information about the northern sand lance's distribution, seasonality, feeding habits, reproductive habits, and relationships with predatory marine mammals, seabirds, and fishes. Recent studies elaborate on its vital contribution to the coastal economy via its role in the food web in the commercial fishing sector (Silva et al. 2021a; Silva et al. 2021b; Staudinger et al. 2020; Suca et al. 2021). One cautionary note, though: gaps in our knowledge of the Atlantic sand lance, the species that is literally underfoot and mostly outside BOEM jurisdiction, could prove important to Federal-state cooperation in managing coastal sand resources and minimizing the collateral impacts of beach renourishment.

Our work focused on exploring trade-offs surrounding sand dredging and its impact on the northern sand lance (*Ammodytes dubius*) and demonstrated that this seemingly simple assessment has wide-ranging implications. Understanding and planning for trade-offs are increasingly important, as US Atlantic beaches need sand due to exhaustion of nearshore resources, rising sea levels, more frequent and intense storms, and other impacts related to global environmental change. Collectively, this indicates three large areas of uncertainty regarding the distribution and abundance of sand lance along the Atlantic Coast. First, sand lance populations fluctuate stochastically in space and time, even within suitable habitats. Second, the community ecology of benthic assemblages on sand is richer and more nuanced than we had thought. We do not yet know how sand lance respond to this variation within a sandy habitat. The third gap in our knowledge, the relationship between the two sand lance species and how they straddle the border between state and Federal waters, remains noteworthy but is outside the focus of this study.

In addition, sea level rise and other issues related to climate change threaten coastal values in all the world's coastlines (e.g., warmer ocean surface waters feeding more powerful coastal storms which can cause heightened coastal erosion, alter species' distribution, etc.) Our model connects the coastal beaches to dredging sites of suitable sands for beach nourishment in the ocean and simulations enable us to explore implications for management under various climate change scenarios. This study provided an opportunity to design a dynamic systems framework based on data gathered and prior knowledge that can be applied elsewhere in the context of decision-making for sand dredging.

2.1 Coastal Beaches—Demand for Offshore Sand

Many beaches along the US East Coast are eroding due to several factors, including more frequent and severe storms along the Atlantic Coast and the rise in sea level accelerated by climate change (Church and White 2011; Parkinson and Ogurcak 2018). Disruption or acceleration of natural sediment transport dynamics can threaten marine habitats, public infrastructure, coastal real estate, and tourism. Coastal beaches, and associated management and renourishment plans, are essential to many local and regional economies.

Erosion also leads to land loss. Sea level is estimated to rise approximately 30–130 cm by 2100 relative to 2000 (Le Cozannet et al. 2017). Some regions will experience greater impacts than others from sea level rise due to associated factors such as local geologic rise or subsidence of land areas relative to global sea level changes, local geological structures, local currents, storm surges (tropical hurricanes), and other factors. Decades of beachfront development removed protective sand dunes, weakened bluffs and banks, and reduced beach widths, resulting in coastal communities being more vulnerable to winds and high waves (ASBPA, 2021). Continued coastal development affects accretion and erosion processes upstream and downstream. Hence, there is a greater demand for sand resources to restore and protect coastal communities and habitats. Beach nourishment through sand dredging is a common engineering solution to reduce the impact of sea level rise and coastal erosion (W.F. Baird & Associates Ltd 2018; Ward et al. 2021). The solution is designed to mitigate the effects of coastal erosion and needs to be performed multiple times.

BOEM's Marine Minerals Program (MMP) is the only Federal agency charged with the authority to convey the rights to dredge the OCS mineral resources. BOEM ensures safe environmental dredging, handling, and placement of Federal sediment resources. The current statistics on coastal restoration are presented in BOEM's MMIS dashboard (BOEM 2021). From 1995 to the present, BOEM has authorized the use of over 178 million cubic yards (MCY) of sand for 64 executed projects sourced from current statistics (MarineCadastre 2021). **Figure 1** shows existing beach nourishment projects, sourced from MarineCadastre. The largest number of projects by state are in Florida while the highest sand allocated in a state is in Louisiana.

Figure 1. Existing beach nourishment projects in the US.
Data sourced from marinecadastre.gov. The size bubbles indicate sand size in MCY.

BOEM relies on scientific research to inform its leasing decisions to ensure safe environmental dredging, handling, and placement of Federal sediment resources. Current technology limits sand dredging to < 30 m deep (modeling for this study buffered dredging to 50 m to allow for technology advancements.) It is becoming increasingly expensive to source sediment for beach nourishment projects along the coast. As suitable areas for sand dredging close to shore become depleted, it becomes necessary to travel further distances to reach locations on the OCS, which increases associated costs (W.F. Baird & Associates Ltd 2018). Resource planning involves a trade-off between minimizing costs and protecting the marine environment and coastal infrastructure. Coastal communities are looking farther offshore for sand resources (i.e., from state waters, which extend 3 nautical miles from the coast, into Federal waters), as nearshore supplies are exhausted, or project success depends on adding to the coastal sediment budget. For example, the coastal beaches around Ocean City, Maryland, have been renourished multiple times since the 1980s, and it has become increasingly problematic to find good, beach-quality sand sources for beach nourishment projects (Coor and Ousley 2019; Jones and Mangun 2001). Beach-compatible sand is a limited resource, and dredging is not sustainable as it does not get replenished at the same rate.

A recent project at Sandbridge Beach in Virginia (USACE 2020) illustrates the various phases of beach nourishment to protect from storm damage. The initial fill started in 2003, with renourishments in 2007 and 2013. Sandbridge has a 13-year renourishment interval. In 2013, about 2 MCY of sand, at the cost of $13.3 million, was placed in the public beachfront from Back Bay National Wildlife Refuge to the Dam Neck Naval Facility, Virginia. The USACE has secured $3.0 million dollars in Federal funding for the project. Hence, in 2020, this beach in Virginia began its new nourishment phase with $20.3 million non-Federal funds.

BOEM and other state and Federal agencies have examined various issues in beach renourishment projects including the significance of grain size (Ward et al. 2021); geospatial shoal identification, classification of sand resources, impacts on fish and resource assessments at critical beaches in Massachusetts (Mabee and Woodruff 2016) and New Jersey (Byrnes et al. 2004). BOEM also created a national database, the Marine Minerals Information System (MMIS), with a state-of-the-art website that provides public access to tools and data related to offshore mineral resources, including an offshore sand inventory (BOEM 2021).

The United States Army Corps of Engineers (USACE) also has a core role to play in beach nourishment. This agency often enters into an agreement with BOEM to execute projects. The USACE was authorized under Section 111 of the 1968 Rivers and Harbors Act (amended later) and several Public Laws. **Figure 2** depicts a typical beach nourishment project undertaken by the USACE.

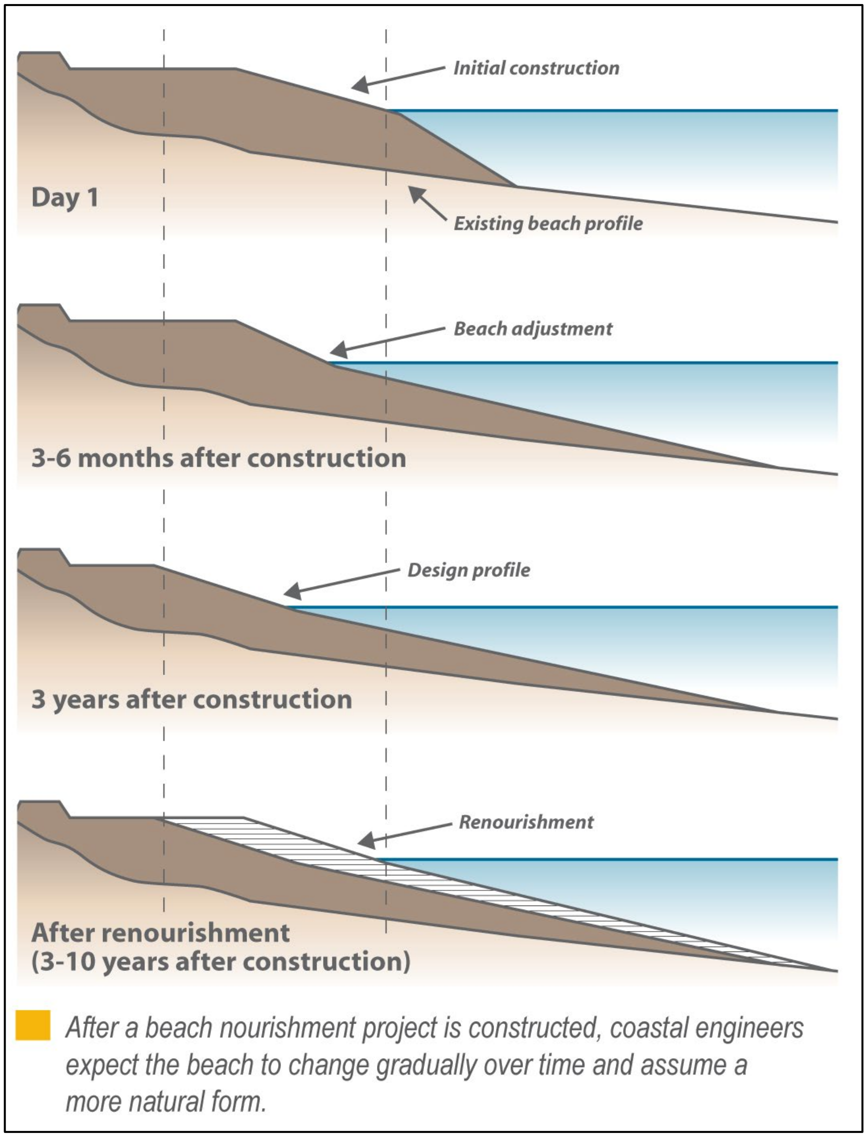


Figure 2. Phases in a typical beach nourishment project.
Beach nourishment sand initial placement and adjustment expected in the project design. Image source: (https://www.nad.usace.army.mil/Media/Images/igphoto/2001018728/) From USACE: During construction of a beach nourishment project, sand is placed so that natural coastal processes can reshape the nourished beach into the desired configuration as intended by coastal engineers. The dry beach may seem "overbuilt" during construction, since sand is often placed on the shore at fairly steep slopes. After construction, it is normal for the newly nourished beach to readjust and change substantially within the first few months. Engineers expect modest waves to move and spread the sediment so that the nourished beach can begin assuming a more natural form. This sediment will continue to move offshore, so that larger waves are prevented from reaching the shore, and along the shore. This movement of sediment, while decreasing the width of the nourished beach somewhat, is not erosion; rather, it indicates that the project is performing as designed” (USACE 2020).

2.2 Examining Sand Dredging Projects Using a DPSIR Framework

The Driver-Pressure-State-Impact-Response (DPSIR) Framework was used for the first consideration of the drivers, pressures, and responses associated with sand dredging activity. A linear, causal structure is useful when presenting indicators and simple feedbacks to policymakers regarding dredging and immediate impacts and trade-offs associated with management decisions. Inferences about longer-term trade-off dynamics require a more realistic, nonlinear mental model, which is described later in this report.

Figure 3 shows the DPSIR structure for this study. For the sake of clarity, arrows are presented in a simplified fashion. In reality, there is a complex interplay of connections between the coupling of natural marine systems with coastal economics, with myriad feedbacks and nonlinear outcomes. A limited set of indicators and their interactions, including feedbacks, are included and modeled in the MIMES model (Section 4). The goal of the MIMES model is to capture trade-offs between commercial fisheries, sand dredging, and sand lance distributions and project possible dynamics through time under alternative dredging scenarios.

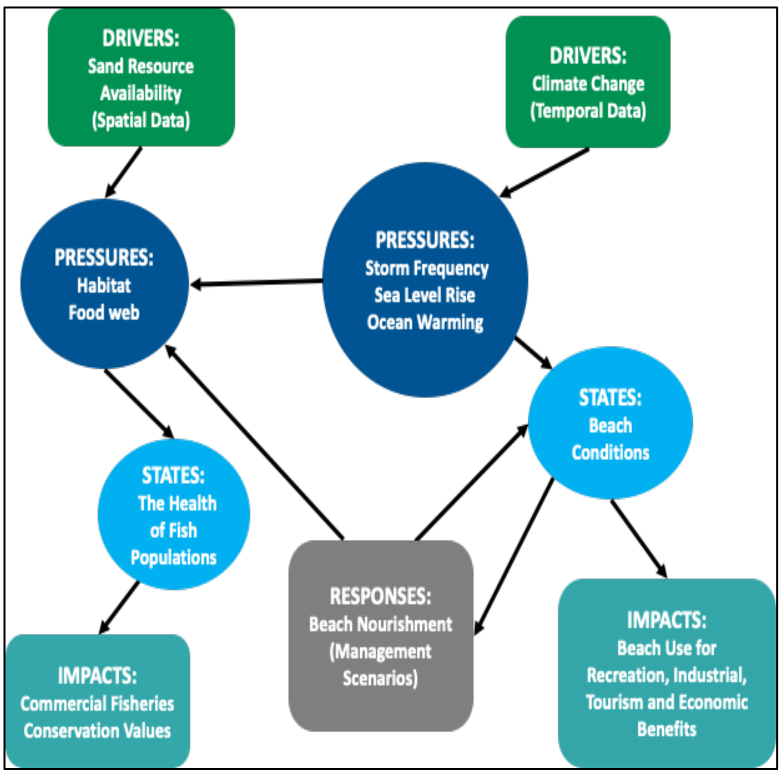


Figure 3. DPSIR framework for examining sand dredging in the context of rising sea levels, and climate change.
Drivers are shown in dark green, pressures in dark blue, states in light blue, impacts in teal, and response in gray.

One important driver in sand dredging trade-offs is climate change (drivers shown in dark green in **Figure 3**), which results in pressures (shown in dark blue) that include sea level rise (IPCC 2021), ocean warming (IPCC 2021), and increasing frequency and intensity of storms (Emanuel 2013). These directly impact coastal beaches shown in **Figure 1**. A second driver is sand resource availability, which relates to dredging pressures on the sand habitat-based food web (Grothues et al. 2021) and species (i.e., sand lance) that depend directly on sand habitat for shelter (Staudinger et al. 2020). Pressures are the mechanisms that cause changes in beach conditions (Cutler et al. 2020; Gopalakrishnan et al. 2017;

Schlacher et al. 2008) and the health of fish populations (or States, shown in light blue) which lead to impacts on commercial fishing and conservation values (shown in teal). Impacts on recreation, tourism, and other associated economic benefits also relate to the human perception of beach quality (de Schipper et al. 2021). Responses (shown in gray) represent beach nourishment projects that need to be assessed and managed (Smith et al. 2009).

There are three major approaches to shore protection to mitigate coastal erosion and flooding. “Hard” structures involve building seawalls, groins, breakwaters, revetments, while “soft” structures include dune construction and beach nourishment (or beach filling) projects (National Research Council 1987). Beach nourishment involves the addition of sand to increase the width or sand volume of the beach; it is widely used to combat coastal erosion. This method is preferred (McLachlan and Brown 2006) because hard structural solutions are more expensive and can result in detrimental effects on adjacent beaches and coastal ecology (Cooke et al. 2012).

The Intergovernmental Panel on Climate Change (IPCC) is the definitive source for climate change impacts, including sea level projections. The IPCC reports represent scientific consensus on climate change science (Pörtner et al. 2019). IPCC proposed four Representative Concentration Pathways (RCPs), which are greenhouse gas concentration trajectories to describe different future climate scenarios. The RCPs represent four possible radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 watts per meter squared) and are labeled as RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, going from best- to worst-case scenario. In Florida, the shoreline is estimated to recede in all IPCC scenarios, including even the most benign RCP 2.6 scenario. Beach nourishment is therefore critical to protect the coast of Florida (Houston 2020).

2.3 CHANS Framework—Sand Dredging and Trade-offs in Different Scenarios

Since they occur at the nexus of society and its supporting ecosystem, dredge impact trade-offs should be examined through the lens of coupled human-natural systems (CHANS). CHANS are complex, with multiple and interacting drivers acting on connected ecological and human communities in ways that vary over space and time. Against this backdrop, effective ecosystem-based resource management requires the ability to consider a range of outcomes over time and the potential for unexpected consequences, costs, opportunities, and benefits. Ecosystem models are of great value to these aims, particularly for decision support (Fulton et al. 2015; Link et al. 2012; Plagányi et al. 2014), with a growing number of practical and applied examples (Dahood et al. 2020; Fulton et al. 2015; Kaplan et al. 2019). The use of such models to help assess trade-offs and foresee surprising outcomes is still in its infancy. Given the unavoidable complexity of the real-world, new challenges across these axes will certainly emerge, particularly considering increasing human needs and global climate change.

Coupled coastal and marine human-natural systems offer clear examples of this challenge, as well as the opportunities for systems models to aid in meeting it. The northeastern coast of the US consists mostly of rocky shorelines (especially in the northern Gulf of Maine) to the north and increasingly sandy beaches south, with diverse, offshore benthic habitats. These habitats are associated with a dynamic set of human interests and benefits, from real estate and water-related recreational opportunities on the beach to recreational and commercial marine fisheries, shipping, and opportunities for renewable energy further afield. Yet the beaches and continental shelf also support a vibrant ecosystem and are vital to a host of marine wildlife species.

Some human and ecosystem needs are mutually compatible, but others are not. Recent research has shown the multiple interconnections and topics in this study of beach erosion and CHANS coupling (Cutler et al. 2020, Gopalakrishnan et al. 2017, Janoff et al. 2020). For instance, the erosion of beaches due to severe storms or sea level rise requires the renourishment of sand to support coastal communities and infrastructure, and there is rising demand to mine sand from the continental shelf for beach renourishment along the eastern seaboard of the US (Benedet et al. 2007, Hayes and Nairn 2004). This mounting need is potentially incompatible with others that rely upon an intact, productive, and diverse sea bottom ecology. Soft-sediment habitats potentially useful for sand dredging also support high levels of biodiversity—with many organisms critical for creating their physical structures across multiple scales—and are critical to ocean processes and ecosystem services (Thrush and Dayton 2002). These areas are foundational marine habitats for a diverse array of marine species and support other human sectors, such as recreational and commercial fishing. Consequently, sand dredging, the marine ecosystem, and a host of other marine-reliant human industries are enmeshed in a web of interactions, feedbacks, and, consequently, trade-offs.

Beaches provide a host of ecosystem services: recreation, flood protection, biodiversity maintenance, fisheries, real estate value, aesthetic, and cultural values. Maintaining them is of great importance but doing so through beach renourishment can also pose a considerable threat to marine ecosystems (de Schipper et al. 2021). Reduction in sand resources can impact benthic community structure directly and indirectly through ecological impacts (Hayes and Nairn 2004). Sand dredging can also affect the outcomes of natural coastal processes (Kelley et al. 2004). Benthic impacts and recovery are variable, spanning from biomass recovery (within about 3 months) to recovery failure (on human-relevant timescales) (Michel et al., 2013). If sediment characteristics such as grain size change due to dredging, the recolonizing organisms will also change, resulting in new community composition (Crowe et al., 2016). There are other potential impacts of dredging that we did not consider here, such as the potential for underwater noise, which can exceed thresholds for wildlife harassment (Reine et al. 2014). Sand dredging can also release contaminants and metals, impact behavior and physiology of marine organisms, and entrain species; the resulting sand plumes can cause smothering and changes in light penetration (Wenger et al. 2017).

There are also other impacts to the benthos that could result in cumulative consequences beyond the risks mentioned here, similar to the diverse ways in which fishing by trawl and dredge can affect marine sand habitats and the larger connected ecosystem (Thrush and Dayton 2002). Moreover, we have focused on only one aspect of sand habitats, impacts on sand lance and their predators, leaving out some complex ramifications, ranging from impacts on system resilience to changes in habitat structure. There is much still to discover about how organisms and habitats respond to, and recover from, benthic disturbance from sand dredging. This is especially true for ecosystem connections across species as these relate to ecosystem services, both in time and at varying spatial scales (Thrush and Dayton 2002). Indirect impacts to habitat and consequences for other species such as important prey could outweigh direct mortality. Ultimately, both direct and indirect consequences need to be considered as fully as possible (Wenger et al. 2017). It is difficult to generalize regarding benthic faunal recovery times following sand dredging as there have been few large-scale studies (Brooks et al. 2006).

Beach renourishment will increasingly be needed for areas besides those studied here, suggesting an escalating need for sand from the OCS (Hayes and Nairn 2004; Kelley et al. 2004). Recent research proposes classifying recent bathymetry data in the US Atlantic shelf and Gulf of Mexico to identify sand shoals (Pickens et al. 2021). The methodology is generalizable for other regions (Pickens et al. 2021). Increasing demand for good-quality sand of appropriate grain size distribution for beach renourishment calls for an opening up of sand resources on the continental shelf with concomitant increases in associated impacts.

The offshore ecosystems that are the source of sand for beach renourishment are, like other ecosystems, highly complex and varied in their behavior. Ecosystems often react in unexpected ways to human activities that support economic development. These surprises can include both lucrative synergies and frustrating trade-offs, the latter carrying potentially severe ecological, economic, political, and human consequences. Rational planning of human activities in nature requires the anticipation of possible hazards and costs, especially those that arise from system complexities and are often unexpected and/or counterintuitive.

In the US, about 13.1 million people living in 319 coastal counties could be at risk from a sea level rise of 1.8 m by 2100 (Hauer et al. 2016). A social trap can occur in sand dredging projects and subsequent beach renourishment. In the case of sand dredging, immediate need by coastal communities alongside immediate benefit to the sand dredging industry promote short-term gains that, in our case, lead to a social trap of sand dredging wherein the benefits to both coastal communities and the sand dredging industry decline over time, but without an alternative to address the societal need. Costanza (1987) argued for an environmental policy approach to social traps by considering the choices as trade-offs. If there is uncertainty in long-term costs, then we should assume the worst-case scenario, place the burden of proving otherwise and additional costs incurred on those responsible for their incursion. While Costanza (1987) also used a sand dredging example to make this case, our work denotes the complexity of such an approach. First, who is incurring the costs? The sand dredging industry is doing the dredging but via projects put forward by the Federal government, which is, in turn, putting forward those projects at the behest of coastal communities. Indeed, as our preliminary work showed, sand demand stems directly from people living in the coastal communities. Thus, the onus is placed on coastal communities.

Prior research has examined both the impact of local wealth of communities as a driver of sand renourishment projects, as well as the need for projects to be of high enough value to attract the sand dredging industry (de Schipper et al. 2021). Any additional fees are likely to only exacerbate inequalities in beach renourishment (Colten 2021; Pilkey et al. 2021). Further, higher costs may allow only certain communities to stay in coastal areas (Gopalakrishnan et al. 2020; Neal et al. 2018) and may encourage changes in local sand nourishment structure (Armstrong and Lazarus 2019; Dean 2018; Fegley et al. 2020), potentially driving a new social trap. Finally, focusing on only economic incentives and values (Gotham 2012; Janoff et al. 2020) excludes a wide range of other ways in which people consider the natural world.

Broadening to other values may offer new pathways for avoiding social traps without incurring new economic costs that only some may be able to pay (Siders 2019). Increasingly, there are issues related to environmental or social justice. Coastal regions that have more socially vulnerable populations may not have funds to renourish their beaches and may have to retreat while richer communities may continue renourishing their beaches until it is economically not feasible in the future.

2.4 Project Goals

As outlined in Section 1, the overall goal of this study is to capture the trade-offs between the timing and location of sand dredging and commercial fisheries, as seen through the lens of sand lance biology. This work incorporates our CHANS understanding of the ecology of the system of continental shelf sand communities.

The decision tool should provide robust data analysis and models to inform sand dredging decision-making while ensuring minimal damage to the offshore benthic community and consequent indirect effects to commercial fisheries. Sand lance provides a significant food source for commercial fishes. The highly valued New England fisheries and other commercial coastal activities rely on sand lance, which in this system includes two fish species dependent on submarine sands. At a minimum, this modeling requires knowing how the flow of ecosystem services is likely to be affected by sand dredging and, ultimately, the associated value chains and the distribution of risks and benefits to coastal communities. It requires spatial data modeling on where forage fishes are likely to be concentrated (potential habitat), and where they actually are at the time that dredging is to occur. We designed an integrated and dynamic model MIMES based on the CHANS framework to explore the ecology of the system of continental shelf sand communities. The model simulation results are presented using a visualization decision tool called Marine Integrated Decision Analysis System (MIDAS).

One of our goals in this project was to work closely with colleagues in BOEM to support trade-off analysis. We aimed to smooth the integration of existing and new approaches, harnessing the best of both. Trade-off analysis depends on the richness and confidence level of the information available, but the information comes at a price. The ultimate trade-off is the price point at the intersection between risk reduction and price containment. Coupling trade-off analysis to whole-system models is a critical step toward Ecosystem-Based Management (EBM). Getting there requires a little bit of extra effort, but the systems approach can ultimately reduce costs and start-up time for new projects and sidestep emergent issues before they become serious problems.

Our project "Productivity and Ecology of Sand Habitats" was conducted from 2019–2021 and aims to model decision trade-offs in borrow area design and impacts to sand lance and commercial fisheries. Our collaborators on this project included National Oceanic and Atmospheric Administration (NOAA) SBNMS, UConn, and the Woods Hole Oceanographic Institute (**Figure 4**).

Our project has the following research objectives:

- Integrate the empirical results flowing from BOEM-funded fieldwork being conducted in concert with our partners.
- Develop a decision support tool to model marine and coastal system dynamics. The integrated dynamic MIMES systems model aims to identify the times and locations of sand dredging with minimal impact on sand lance, the sand shoal habitat, and its ecosystem.
- Reveal likely impacts to commercial fisheries based on sand lance biomass dynamics, and predator-prey relationships.
- Design trade-off scenarios to minimize impacts to commercial fisheries and optimize sand dredging for beach renourishment. Elucidate risks associated with our uncertainty around sand lance, sand shoal habitat, and their ecological roles as they relate to sand dredging and its impacts.
- Visualize decision trade-offs in MIDAS to relate our insights and findings to best guide sand dredging strategies that are minimally damaging to offshore benthic communities.

Figure 4. A spatial decision support system for trade-offs between sand lance and beach nourishment framework.

The project aims to answer these questions by employing a dynamic systems model, MIMES, to explore outcomes and provide decision support for the study area to model scenarios and anticipate impacts of sand dredging. MIMES (Altman et al. 2014; Boumans et al. 2015) models will incorporate sand lance aging data and other new field data from the Sanctuary-led work. The MIMES analysis of the trade-off scenarios of borrow area designs and impacts can be used to infer potential to specific commercial fisheries, highly migratory species, and species of concern, based on their known dependence on sand habitats and the prey species that occur there, particularly the sand lance. This process will leverage an existing MIMES implementation for Massachusetts Bay and partnerships with the National Marine Sanctuaries Program and BOEM, with specific goals to aid BOEM in developing a sand dredging strategy and options that minimize impacts on the sand lance and critical commercial fisheries (**Figure 4**). Expected outcomes of this study include a fully functional MIMES/MIDAS (Gopal et al. 2015; Pitts et al. 2020) model to describe and visualize scenarios and determine different impacts.

3 Study Area and Data

SBNMS, Woods Hole Oceanographic Institute (WHOI), UConn, and BU partnered to gather much of the empirical data needed to address questions related to sand lance for this study. Dr. David Wiley of SBNMS led field operations aboard the R/V Auk that included sampling for sand lance on Stellwagen Bank (in collaboration with the US Geological Survey) and studies of their predators including marine mammals (i.e., humpback whales) and seabirds (i.e., great shearwaters). Drs. Joel Llopiz and Justin Suca of WHOI led work on growth, feeding, and other aspects of the biology of northern sand lance. Dr. Hannes Baumann and his students at UConn led work on the early life history of northern sand lance and their vulnerability to climate change. The Kaufman Lab at BU continued its work on the feeding habits of sand lance as inferred by stable isotope analysis and led the comparative morphological study of northern and American sand lance. BU utilized data streams from the field (including the above work and National Marine Fisheries Service [NMFS] fishery-independent surveys up until 2008) and other sources as inputs to a dynamic model for sand lance distribution and abundance. Here we describe the study areas used in our dynamic modeling approach to explore sand dredging scenarios.

3.1 Study Area Selection

We employed our systems model approach in two locations, shown in **Figure 5**: one for Long Beach in Ocean County, New Jersey (NJ-MIMES, shown in pink), and one for SBNMS and Massachusetts Bay off Massachusetts (SB-MIMES, shown in blue). Two key contour lines shown in **Figure 5**. The marine boundary of the data collection area is the deepest extent of anticipated dredging activities (i.e., 50-m contour line) although 30 m is currently the deepest extent of existing dredge activities (Pickens et al. 2020). The contour line was derived from the Bathymetric Contours layer provided by NOAA. Note that dredging is not permitted in SBNMS due to its protected status. Beaches in New Jersey (**Figure 5**) have been essential for recreation for decades, with related infrastructure development starting in the mid-1800s and beach renourishment starting in the 1950s (Byrnes et al. 2004).

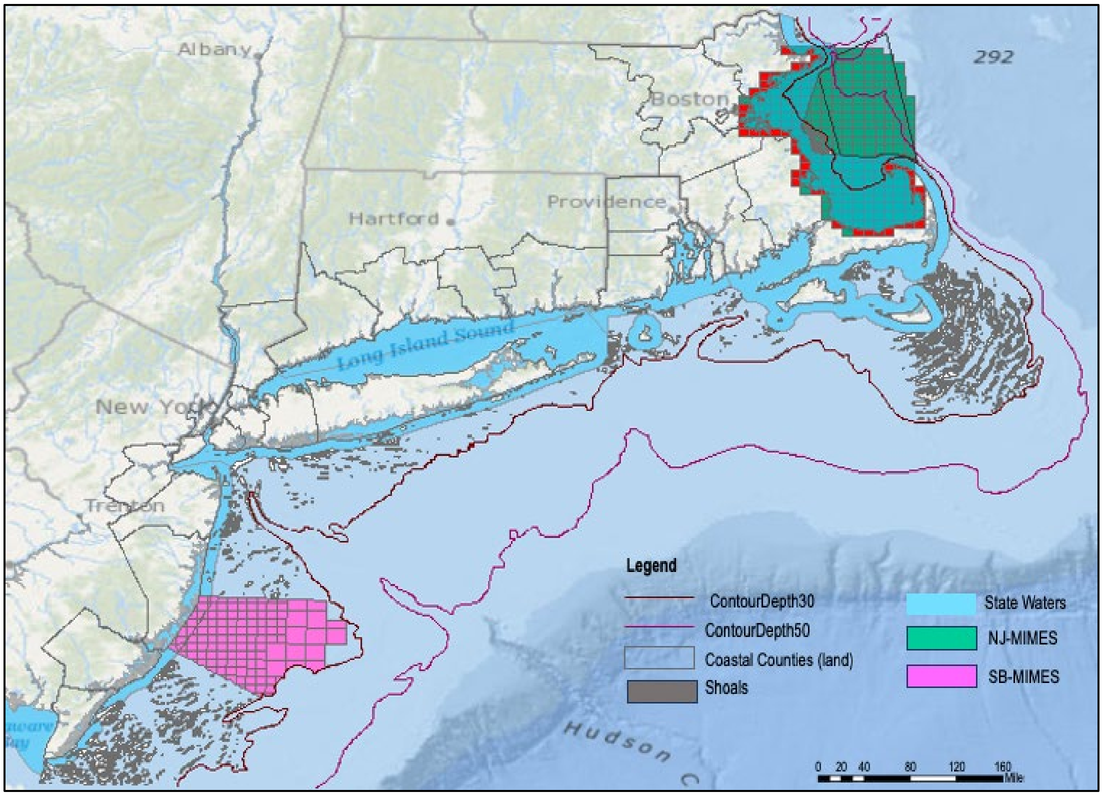


Figure 5. The Long Beach County (NJ) and Mass Bay/SBNMS (MA) spatial extent.
The two study areas modeled in MIMES are shown in NJ (pink) and MA (blue). Two key contour lines on the map are 30-m and 50-m depths. Contours extracted from NOAA's bathymetry.

The reason for adding the 90-m contour line is to account for a substantial portion of the adult northern sand lance population inhabiting water deeper than is typically targeted for sand sourcing, particularly in the Mid-Atlantic (**Figure 6**). It is possible that this provides some buffer against dredging impacts on the total population.

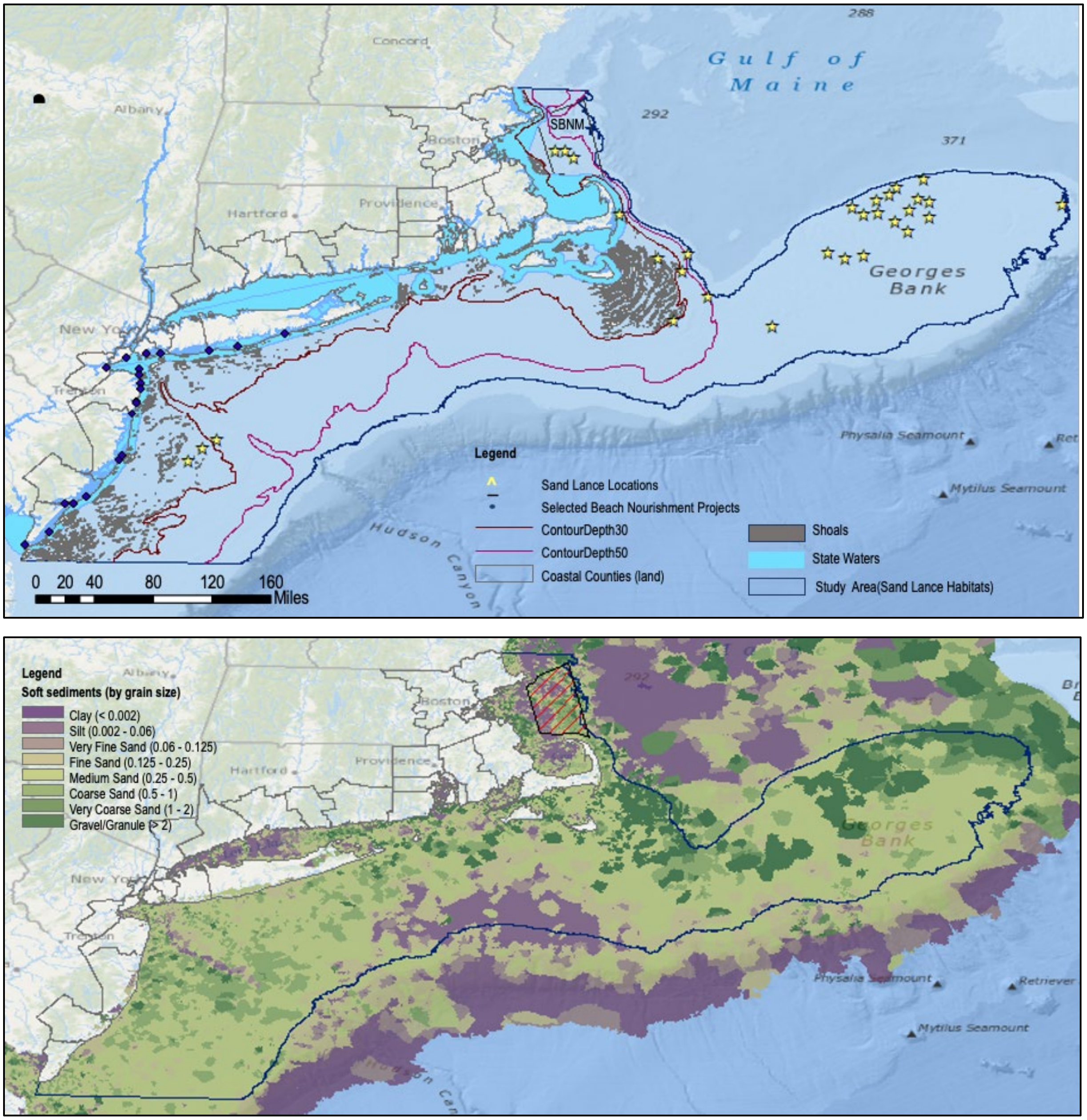


Figure 6. Inputs to MIMES: Long Beach County (NJ) and SBNMS (MA).
Top panel shows sand shoals (potential areas for sand dredging) in gray, while stars indicate locations of sand lance from prior NMFS scientific trawl surveys. Lease areas in New Jersey are shown in purple. Areas for renourishment are dots on the coast, the quantity is measured in MCY. The lower panel (sourced from TNC) details sediment type including sand. Maps include depths > 50 m to include sand lance habitat.

3.2 Data Selection and Integration

Data sources are shown in **Table 1.** The spatial and temporal resolution of data differs across sources. MIMES models can accommodate these different resolutions and can output results in terms of marine and terrestrial polygons, described in **Section 4.1**. Data sources include the Northeast Regional Ocean

Council, and Mid-Atlantic (MARCO) data portals. Remote sensing data (i.e., sea surface temperature) was sourced using Google Earth Engine.

Table 1. Data layers used in designing MIMES models

Data	Time Period	Data Source
Sociodemographic Data	2019	US Census: Census tracts
Soft Sediments (Grain Size)	2016	The Nature Conservancy (TNC) raster processed data
Sand Lance (Forage Fish Data)	1968 to 2008	NEFSC surveys—trawl surveys to estimate sand lance and other fish population
Public Beaches	2021	Location data compiled from Google Maps
Beach Nourishment	1960s to 2020	West Carolina Beach nourishment database
Sea Water Depth	2020	NOAA satellite data at 3 arc second to derive ocean bathymetry
Sea Surface Water Temperature	2014 to 2019	NOAA satellite data at 0.08 arc degrees to estimate surface and model temperatures at multiple depths
Chance of Occurrence of Sand	2015	TNC data at 500 M raster resolution
Soft-sediments Grain Size	2015	TNC data used for estimating MIMES inputs on sand characteristics
Bathymetric Contours	2018	NOAA Office of Coastal Management; the Digital Elevation Model (DEM) utilized was the Global Multi-Resolution Topography (GMRT)
Distance to Land	2020	Estimated using spatial data
Zooplankton Biomass	2019	NAUPLIUS data at 0.25 arc degree showing biomass in mg C m-3

3.3 MIDAS—Visualization of MIMES Model Outcomes

MIDAS is our process for making MIMES output user friendly for decision-makers. Developed to support marine spatial planning (Patel et al. 2011), MIDAS is used to communicate model results and support understanding of related trade-offs and outcomes. Using MIMES results, MIDAS can develop geographic information system (GIS) layer call-ups and overlays, and depict and contrast alternative outcomes of projected scenarios through visualization such as graphs and heat maps. MIDAS is designed to process and visualize large data sets, integrating raster, vector, survey, and other qualitative and quantitative data. In this study, MIDAS is utilized to facilitate a graphic user interface and dynamic dashboarding (**Figure 7**). MIDAS developed in tandem with MIMES is hereafter referred to as the MIMES-MIDAS approach (Altman et al. 2014).

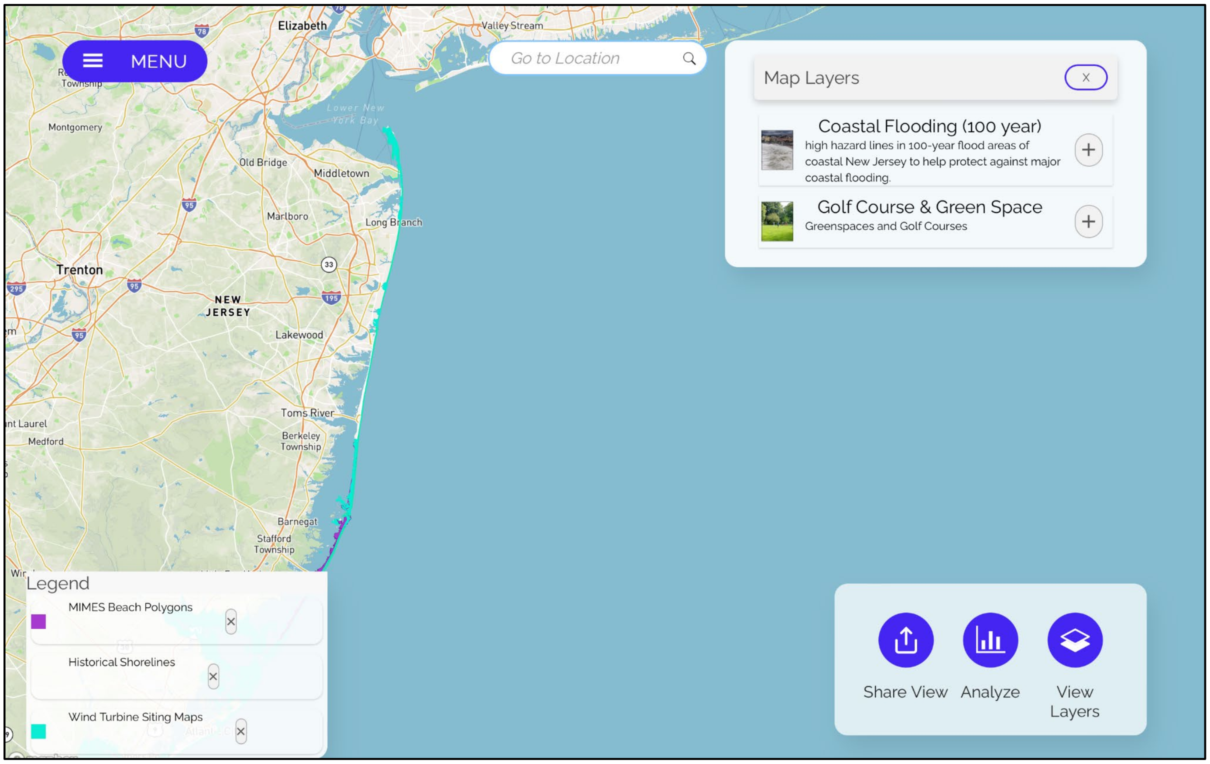


Figure 7. MIDAS user interface displaying maps and outcomes.
MIDAS users can choose to view layers or analyze the results of MIMES scenarios.

MIDAS uses a combination of open-source technologies to empower the data management, collection, and decision-making processes. For data loading, MIMES provides the capability to output data in several formats. A commonly used format, Comma Separated Values (.csv), provides an easily transferable format that many data processing and management tools can utilize. As the data output from MIMES covers a wide range of daily time steps, indicators, spatial locations, and scenario configurations, the total combination is very large (see **Section 5**). The data processing of MIMES outputs is written in a combination of open-source data processing tools based in Python. Once processed, data is loaded into a database (Postgresql) and optimized for analysis and access. Other data sources are then loaded into a combination of database and storage techniques in order to blend these other data with the core MIMES output to aid in synthesis and analysis. For example, sociodemographic geospatial data from the US Census may be blended into the results to add context to beach community stakeholders. **Figure 7** shows the MIDAS interface displaying maps and outcomes.

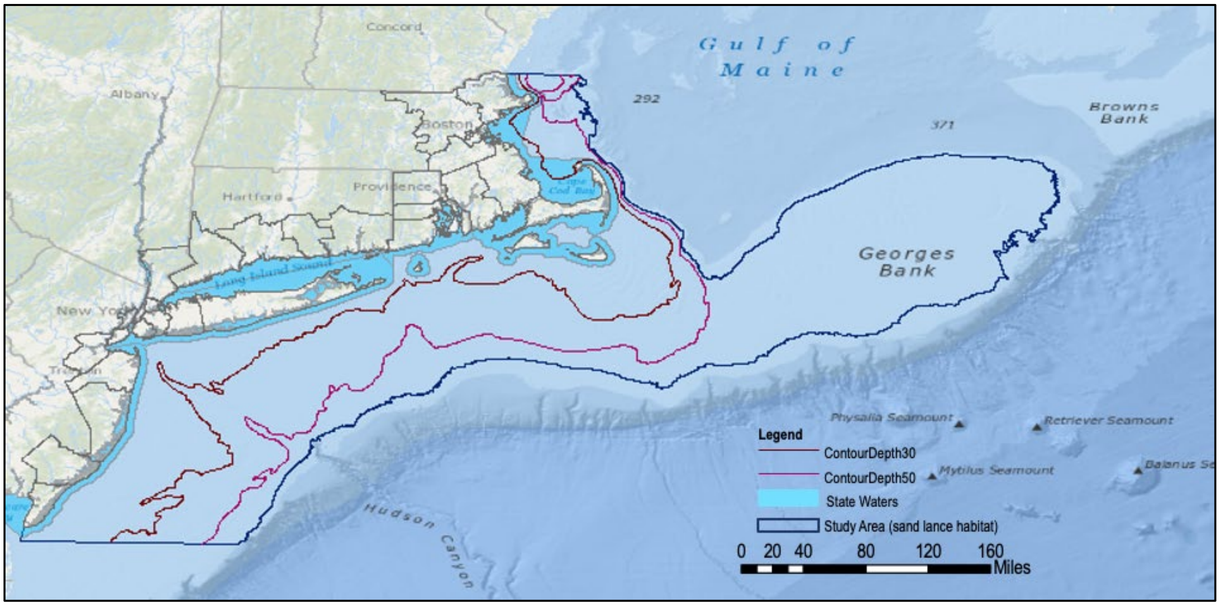


Figure 8. Water depth below and above 50-m contours in state waters.
Coastal counties are sourced from the US Census Bureau; contours are from NOAA. The area enclosed by the 50-meter contour line is shaded in blue.

4 Applied MIMES Systems Modeling

MIMES, the core instrument employed for this study, is coded in a computer metalanguage called SIMILE, which was designed specifically to model systems with a large amount of feedback and nonlinear behavior. Broadly, the MIMES model is structured around spheres, with four forms of capital describing how human and natural system components contribute to human well-being (**Figure 9**). Comprehensive, holistic production and impact functions determine how ecosystem services are generated from the overall system, including feedbacks. Demand profiles designate how the demand for services varies across different groups of people (Boumans et al. 2015). These model components are discussed in more detail in **Appendix A**. Collectively, the results are visualized and made available to the MIDAS platform.

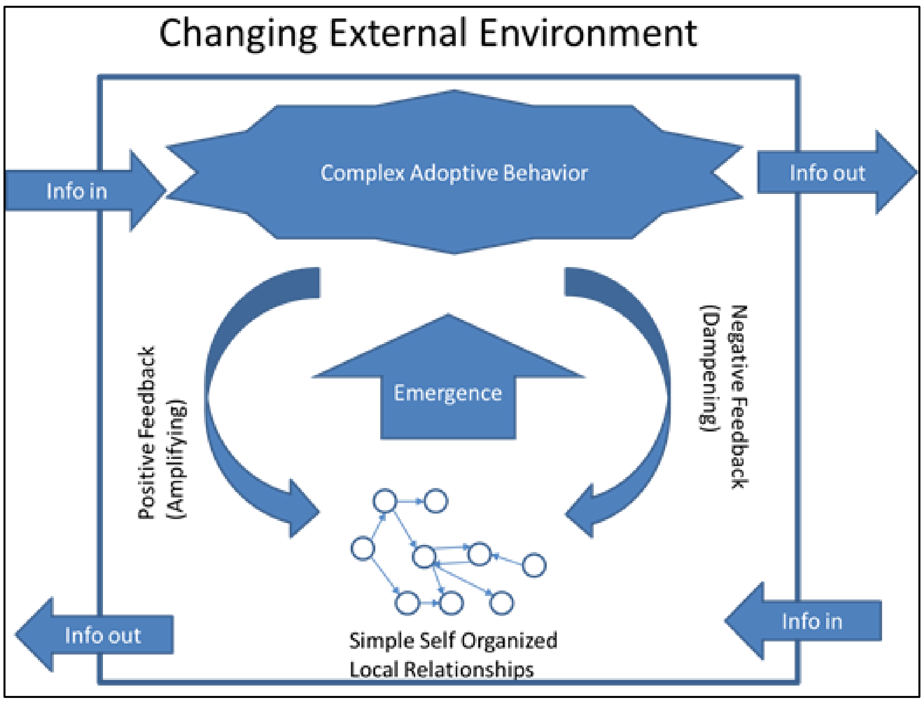


Figure 9. The concept of a dynamic model in predicting complex systems.

4.1 Building a Fully Operational MIMES Application: Unit Model vs. the Spatial Model

MIMES was used to capture trade-offs in the practice of beach nourishment while dredging sand from the ocean floor for two locations, Long Beach in Ocean County, New Jersey, and SBNMS in Massachusetts Bay. From here forward, we refer to our MIMES for New Jersey as NJ-MIMES and that of Massachusetts Stellwagen Bank as SB-MIMES. The New Jersey study area is critical given its history of sand demand and likely increasing needs in the future. In contrast, the demand for sand in SBNMS, Massachusetts Bay, and the surrounding area is relatively minimal (although likely to increase). Still, we have a much better understanding of this region's biology, ecosystem, and human dimensions due to prior extensive research done by our team partners in the SBNMS and the current BOEM collaborative research (**Figure 4**).

Therefore, developing both a NJ-MIMES and a SB-MIMES is important to

1. Leverage an area of existing interest for sand dredging alongside extensive scientific knowledge and data

2. Establish repeatable processes to build potential use cases in other areas

3. Provide a framework to build CHANS models in future marine and coastal ecosystem work

Systems models built in MIMES are dynamic and spatially explicit. For NJ-MIMES, the spatial extent, or model arena, is scaled out from Long Beach County, with upper and lower spatial boundaries running from the coast out to the 90-m depth contours (**Figure 10**). The SB-MIMES arena boundaries are Cape Cod to the southeast extending north to Gloucester in Essex County, MA. We then divided these model arenas into a grid of smaller cells, representing the model's spatial resolution, i.e., the more and therefore smaller cells in the grid across the model arena, the greater the model's spatial resolution. We refer to these cells as "MIMES polygons" or "polygons," which are 4 x 4-km cells for both NJ and MA. For our work here, we differentiate coastal counties where people reside. Thus, we needed two different sets of polygons, one for human communities (the "upland" polygons) and one for the marine ecosystem (the "marine" polygons).

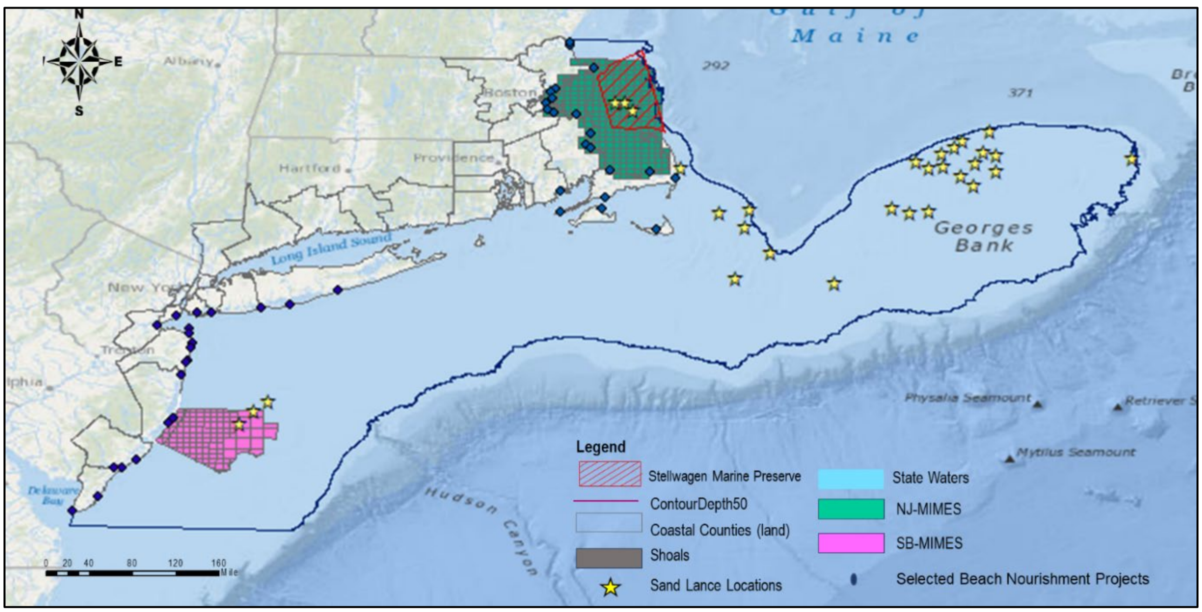


Figure 10. NJ-MIMES and SB-MIMES spatial extent and resolution.
A map of the relevant sections of the coast, the NJ-MIMES spatial extent, and SB-MIMES, encompassing all polygons, outlined and labeled in black. Areas for renourishment are blue diamonds on the coast, and sand shoals (potential areas for dredging) are in yellow (see text below).

We define the upland polygons for NJ-MIMES based on the 12 Census Bureau tract groups containing or bordering the beaches. Due to the more considerable coastal extent, the SB-MIMES has 61 upland coastal communities defined by overlaying MIMES squares on a community map of Massachusetts block groups with oceanfront with a beach feature. For the marine polygons in both NJ-MIMES and SB-MIMES, we overlaid a "MIMES grid" of polygons on the remaining marine model arena. This grid is based on BOEM aliquots in Federal (offshore) waters amended with a similar grid for state (coastal) waters. These are roughly 4x4 km for SB-MIMES and for areas closer to shore in NJ-MIMES, while they are 8x8 km further offshore (given that sand shoals impacted by dredging are more often in these nearer waters (**Figure 11**). These polygons are randomly assigned a reference number for use in the model in NJ (**Figure 10**); they are directionally labeled north to south in SBNMS.

We combine the cells from the marine and upland polygons to create a comprehensive model of CHANS interactions. **Figure 11** shows the NJ-MIMES, with beach locations on the left panel and the corresponding MIMES squares on the right. The temporal dynamics of MIMES vary from daily to yearly time steps. MIMES simulates daily and annual time steps to capture system dynamics relevant to each context over time. For example, daily fluctuations in sand lance biomass are on a different time scale than the annual beach renourishment decisions. The latter coincides with the yearly renourishment decisions undertaken by coastal communities.

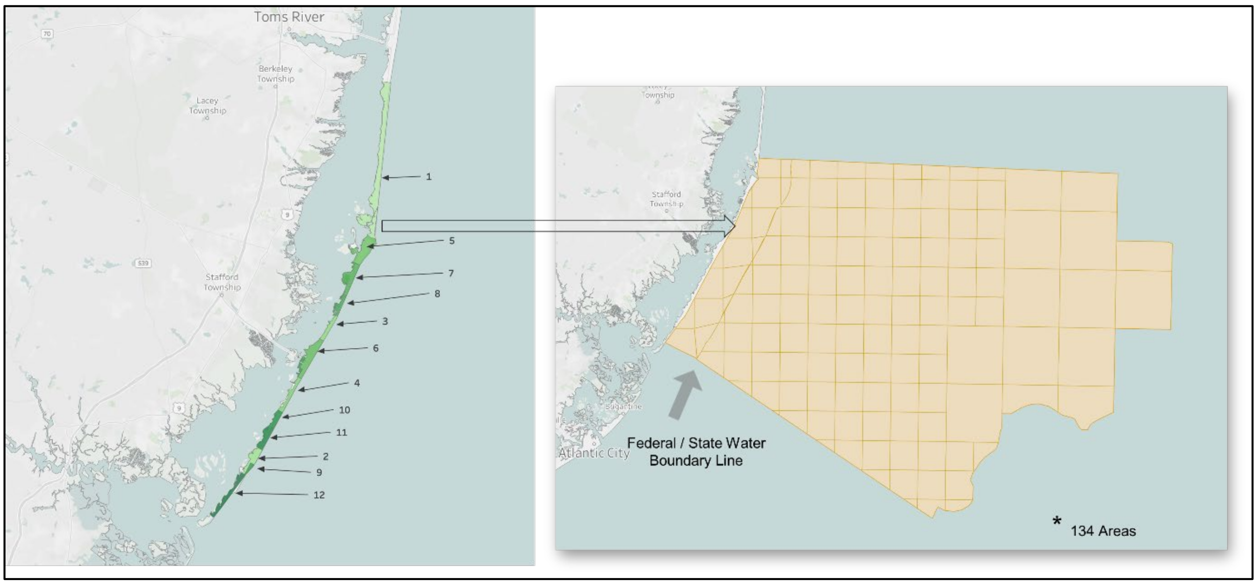


Figure 11. NJ-MIMES study area beaches and corresponding MIMES polygons.

Each polygon includes a unit model (Fitz et al. 1996). Connecting these unit models builds the fully functional spatial model (**Figure 10** and **Figure 11**). Here we describe the unit models and their integration to form the spatial model. We provide descriptions of data inputs and model equations in the Supporting Information (**Appendix A**). In both NJ-MIMES and SB-MIMES, all polygons have a similar underlying unit model structure, one for upland polygons (coastal communities and beach renourishment locations) and one for marine polygons (sand dredging and sand lance locations). The underlying unit model is similar in that both upland and marine polygons have the same underlying unit model. However, they are parameterized differently in each case to reflect location differences in the real world. For example, each marine polygon has a similar unit model of the marine ecosystem, sand dredging potential, and oceanography. Still, defining characteristics of those aspects may vary from polygon to polygon; for example, the polygons have differing amounts of sand, water depth, biomass of sand lance, and/or resident predatory species.

Parameterization of the models makes use of the best available data that can be gleaned from published work and through data portals. Models, such as the one we developed, require many of these data inputs, which are not always available or not at matching space-time resolutions. Confidence in model results is weighted against the quantity and quality of the data we collected to inform the simulations. **Appendix A** as a section on model "uncertainties." Users can interpret MIMES model results in each scenario context with a specification of indicator variables. We can keep improving the confidence in the model results addressing these uncertainties. As better (fine-scale) data is collected or our scientific understanding of the process improves, MIMES can be revised to reduce the model uncertainty.

MIMES simulates at a daily time step to capture dynamics over time. The ecosystem and sand dredging operations occur daily in both models. However, the initiation for renourishment of a beach operates on a yearly time step. Collectively, all results are aggregated to annual indicators. To assess how outcomes evolve realistically across space and time in the full MIMES, the unit models in each polygon connect with the unit models in neighboring polygons by relationships and flows, such as larval dispersal across marine and sand dredging trips between marine and upland polygons. In this way, the polygon unit models "communicate" with one another on biology, and ecology via defined relationships, resulting in the model being dynamic across space. Sand dredging and beach renourishment are other modeled processes where the unit models in each polygon connect in the fully implemented spatial MIMES; these modeled process flows are the main communication channels between the upland and marine polygons in both NJ-MIMES and SB-MIMES.

Appendix A shows all model equations in MIMES developed based on prior published studies. MIMES includes over 21 model equations to set up the system dynamics in different scenarios. The scenario model parameters, validation, and tuning processes utilize all current data and prior published studies. Therefore, we can provide a scalable, science- and data-driven framework for modeling sand lance dynamics and benchmark the impact of sand dredging operations based on MIMES.

Each unit model in MIMES is designed to address a set of questions. The beach unit model to simulate upland polygons is designed to include the dynamics that enter the decision-making process when the following questions are asked:

- Will this beach ever be considered for a nourishment project?
- What is the preferred volume of sand on the beach?
- How much do we like, or can we afford to overfill the beach beyond its preferred volume?
- What is the expected period of organizing a nourishment project (raising the money, securing the permits, and organizing the work)?

The marine unit model simulates dynamics of a sand lance population within habitat conditions, and is designed to address the following questions:

- What is the effect of dredging on sand lance populations?
- What is the effect of habitat destruction on sand lance populations?
- How do sand lance populations contribute to commercial and conservation interests?

Sand lance model considers life cycle, mortality, and predation pressures as well as dispersion of sand lance larvae. Relevant equations in each unit model and uncertainty issues are discussed in **Appendix A**.

4.2 Coastal Communities and Sand Resource Demand

The upland polygons and their unit models represent beaches and adjacent urban areas (e.g., human communities with roads and buildings) in both NJ-MIMES and SB-MIMES. Beach areas in these polygons are parameterized for medium elevation, slope, type(s) of sand, current and preferred sand volumes, and short- and long-term erosion rates (Hapke et al. 2010). Short-term erosion rates indicate events that remove sand quickly, such as major storms, whereas long-term erosion signifies changes due to chronic impacts, such as sea level rise. Long-term rates of change are calculated using all shorelines, and short-term rates of change are estimated using the LiDAR (which stands for light detecting and ranging) shoreline and the historical shoreline, which will produce an assessment for a 25- to 30-year timeframe.

We characterized the beach and urban areas of the 12 upland unit models for NJ-MIMES. GIS data from 2 m above sea level contour to 5 m below sea level aided in determining medium elevations and the slope in the beach polygons. The TNC Soft Sediment map provided estimates for the type(s) of sand (grain size), and the USGS data offered short- and long-term erosion rates. Beach profiles published in the NJDEP (Farrell et al., 2016) report supplied initial and desired sand volumes (**Table 2**). Within these beach areas, we determined where renourishment happens, which further helped delineate drivers of sand demand. For this, we identified renourishment projects in each unit model's beach area by overlaying previous or potential future sand projects from the BOEM and the West Carolina Beach nourishment databases.

MIMES input data consists of the location of the renourishment projects. The next step is data parameterization to derive the location and timing of renourishment projects. For this, we further characterized these areas in MIMES by the short- and long-term erosion rates in each area from USGS data sources (**Table 1**), which denote when beach sand is depleted. Short-term erosion rates likely indicate short-term events, such as major storms, whereas long-term erosion signifies changes due to chronic impacts, such as sea level rise. However, beach renourishment may be enhanced by including more complex community and political interests. These drivers would require further parameterization of the renourishment areas in the model, discussed in subsequent sections.

Our initial scoping of where and when previous sand projects occurred revealed that erosion rates are not the sole indicator of beach renourishment projects. Indeed, they have only a slight positive relationship with columns of sand used in renourishment as seen in **Figure 12**. We suspected that additional drivers of sand demand stemmed from the local human community. To evaluate this, we examined census tract data to determine the local average density of people in each of the 12 coastal beach areas. This data analysis partially explained our insights on erosion rates: beaches with higher erosion rates but no local human communities do not witness beach renourishment. However, human population density in the census tract is not the sole driver in beach renourishment. We found a more substantial relationship between the volume of sand and the average house value in the census tracts (**Figure 12**). Collectively, we found beaches were more likely to be renourished if they were also proximal to areas with more people and those with a higher local home value. In all estimations, we included erosion rates.

Table 2. Characteristics of the beach communities used to derive renourishment indices in each upland unit model in NJ-MIMES

#	Erosion Long-term *m/yr*	Erosion Short-term *m/yr*	Area Urban *km²*	Area Beach *km²*	Elevation Median *m AMSL*	Elevation Range *m*	Beach Slope *% rise*	Beach Length *km*	Beach Grain Size *mm*	Volume of Sand Desired (initial is 0) *CY*	House Value *M $*
1*	-0.24	1.45	10.5	5.2	-2.1	7.8	0.02	15.7	0.45	100	0
2	0.16	-0.57	1.5	0.9	0	6	0.15	1.7	0.41	120	0.8
3	0.33	-0.04	1.7	0.7	-2.95	6	0.12	3.0	0.35	300	1.50
4	-0.55	-0.85	1.5	1.5	-0.1	6	0.29	3.9	0.27	250	0.82
5	-1.83	-1.09	1.1	2.9	-1.6	8.4	0.01	3.4	0.38	200	0.96
6	-0.19	-0.04	3.1	1.6	-0.1	7	0.25	4.4	0.34	75	3.23
7	-1.13	-0.66	2.5	1.0	-0.1	6.9	0.60	3.4	0.34	175	1.17
8	-0.25	11.43	3.5	0.6	-2.25	7	0.05	2.2	0.22	200	1.50
9	-0.47	-0.22	1.1	1.0	-3.4	6.8	0.06	1.4	0.28	120	2.80
10	0	-0.53	1.3	0.9	0	6	0.10	1.8	0.24	225	0.78
11	-0.99	-0.95	0.8	1.2	0	7	0.28	2.5	0.24	200	0.81
12	-6	-2.31	2.1	6.5	-1.9	7.8	0.01	5.0	0.37	175	0.71

* Note: the first community is an undeveloped stretch of beach.

Erosion rates alone could not explain the renourishment model. Some beaches that experienced repeated, expensive renourishment did not have the highest erosion rates but had a combination of erosion, human population density, and wealth. To summarize, a systems approach that examines multiple drivers is necessary to model and predict beach renourishment.

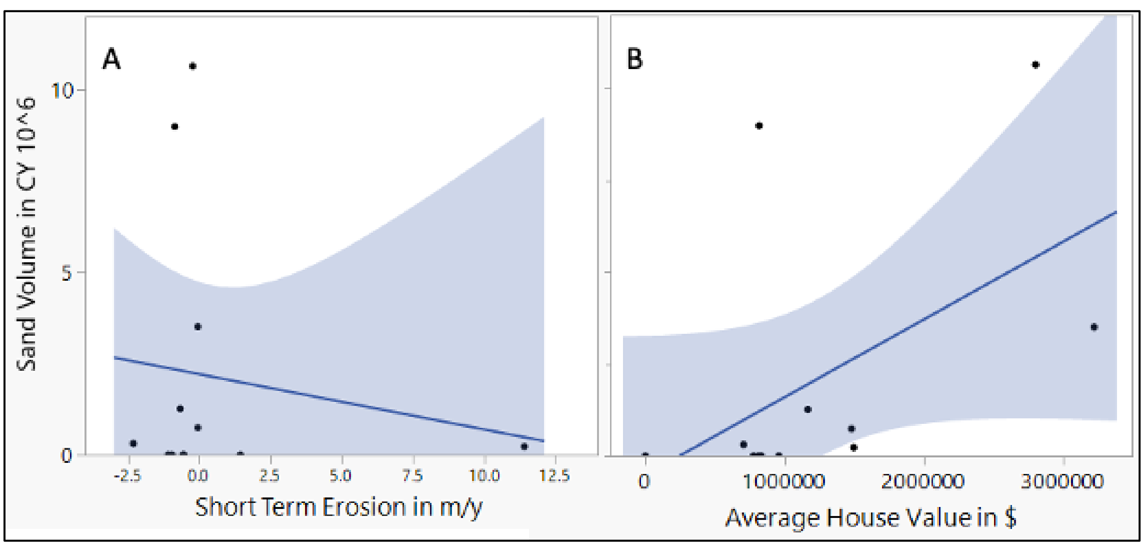


Figure 12. Comparison of potential drivers of sand volume used in beach renourishment projects in the New Jersey study area.
Panel A: Relationship between cubic yards of sand volume (y-axis) and short-term erosion rates. Panel B: Relationship between sand volume (y-axis) and average local house value (x-axis). Shaded areas indicate confidence in the fitted lines. These graphs are suggesting that nourishment projects are most likely to happen when erosion rates are still moderate and housing values are high.

Together, the upland unit models' urban and beach areas drive demand for sand via a combination of erosion rates on the beaches and by population density and home value (as an indicator of wealth) of the urban area (Hapke et al. 2013; NJBPN 2018). We define *an index of urgency in beach renourishment* using this combination of factors (*Equations 1 and 2* in **Appendix A**). For this index, we first estimate erosion rates in each upland polygon that reduces the amount of current sand. We selected a threshold of preferred sand volume to gauge if the current sand volume drops below the preferred sand volume. The difference between the two is the sand deficit. An incurring sand deficit is then considered alongside the local human population and wealth, which define the index of urgency. The NJ-MIMES and SB-MIMES systems model rank beaches with a sand deficit based on an urgency index and initiate beach renourishment in the polygon with the highest index of urgency first. The models also keep track of how long a beach has a sand deficit but is not renourished because other polygons "jump the line" due to higher urgency values (i.e., a polygon's exposure).

Given these findings, we characterized urban areas alongside beach areas in the upland unit models in both MIMES models. The beach areas included indicators of erosion, while the urban areas included local human population density and home value based on the US Census. The census data model incorporates the status of the onshore human communities in the urban areas to adjust the sand demand projects appropriately. Therefore, urban and beach areas together drive demand for sand based on population density, home value as an indicator of wealth, and erosion rates (**Figure 13**). Additional indicators are likely also important but beyond the scope of this work (see Section 7.2 Future Research).

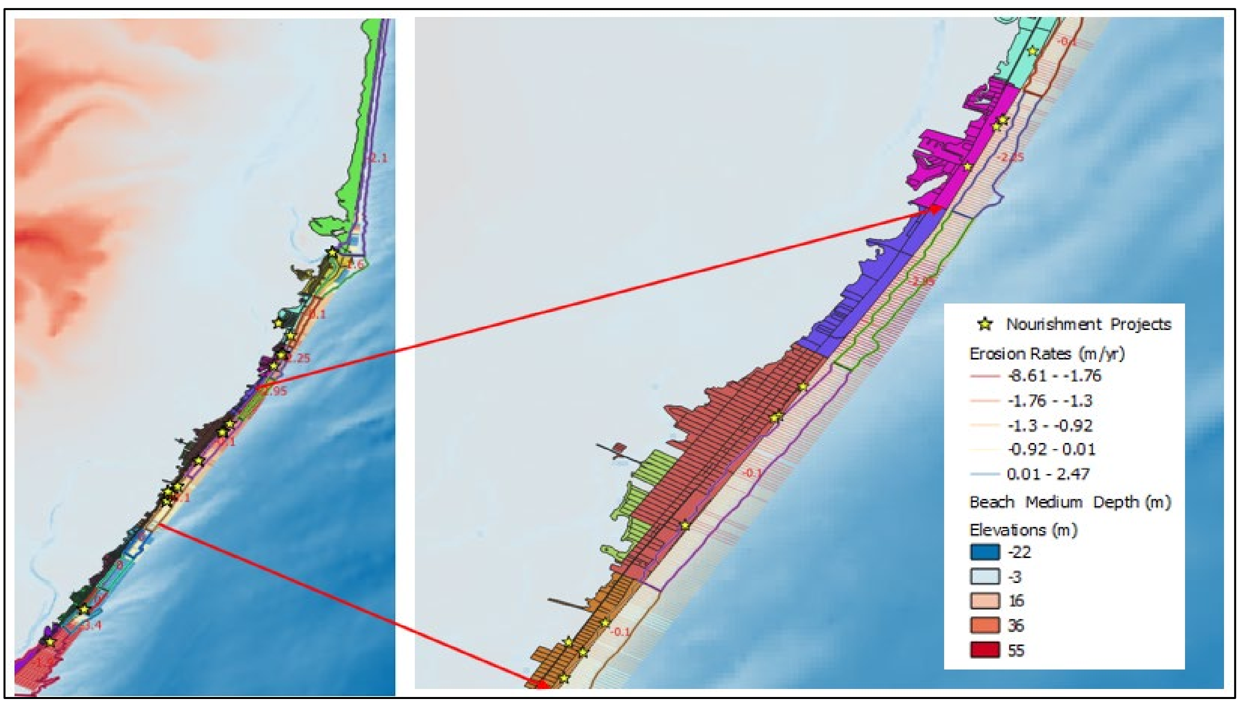


Figure 13. Upland areas simulated by the urban unit model (different colors) for NJ-MIMES, characterized by erosion rates (fine lines extending into the beach).
The left panel shows the map representing Long Beach, Ocean County, New Jersey; the right panel shows the census tracts defining the municipalities on the island. Elevations are shown surrounding the polygons.

4.3 Marine Sand Shoals

The upland polygons and their unit models represent beaches and adjacent urban coastal areas (**Figure 13**). For this work, the critical element of the marine polygons is the sand shoals (Pickens et al. 2020), which are essential both as potential areas to be mined for beach renourishment (i.e., "borrow" areas) and as sand lance habitats. These are parameterized by (1) water depth, (2) amount of sand, (3) type of sand (grain size), and (4) distance to renourishment projects on the coast. We also defined the volume of sand in each marine polygon, but as there is no data on the depth of sand in the shoals, we assumed a standard sand depth of 2 m and multiplied this by the area of sand shoals in each polygon. Each polygon can also restrict the potential for sand dredging of these borrow areas via the taboo parameter, which can be set from 0 to 1. At 0, this parameter is essentially off, and the area is open to sand dredging, whereas, at one, it is fully closed to any dredging. For values between 0 and 1, sand dredging is permitted to that percentage of the total sand resources there (e.g., a taboo of 0.4 allows sand dredging to continue until 40% of sand resources in that polygon are removed). We note that there are currently no replenishment rates for marine sand resources due to lack of data and the fact that many offshore sand areas in our study areas are relic shoals and do not replenish on time scales of the model.

For factors (1) and (2) above, we first determined how much of defined sand shoals were in each MIMES polygon by using the MIMES grid to clip data on locations of sand shoals. We then noted the average depth of water of the sand for (1). For (2), there is no data on the depth of sand in the shoals, so we assumed sand shoal depths of 2 m, and thus by multiplying the area of sand shoal in a polygon by 2, determined the total volume of sand in each MIMES polygon. This assumption around sand depth must be made given the lack of information on the depth of sand in the sand shoals. It is an area for further analysis and can be updated if new data on sand depth becomes available.

For factors (3) and (4), we determined the center point of the proportion of a sand shoal within the MIMES polygon and created a file of these centers. To select (3) sand grain sizes, we used the center points to sample the grain sizes from the TNC soft-sediment data. We took all the resulting sample grain sizes and grouped them into sand size ID categories (0.1–0.2 mm grouping), of which there were 57 total, from 0.15 to 4.71 (0 is there is no sand; 0.15 is very fine to almost gravel at 4.71, **Table 2**). This step provides the grain size ID by potential borrow area, based on BOEM shoal data and TNC grain size information. Sand borrow areas in the MIMES polygons were allowed to have multiple grain ID numbers to denote different types of sand in that polygon. Polygons were allowed up to seven different IDs, as the area with the largest number of ID numbers had seven (although this can be changed if needed in the future). For (4), distance to renourishment projects, we calculated a distance matrix from all center points to all renourishment areas. We only kept distance areas that included nourishment areas to a borrow area (i.e., we discarded any distances borrow to borrow).

Collectively, these indicators are associated with the potential borrow area in a marine unit model; variables including depth, sand volume, distance, and grain size determine if the borrow area is useful to a renourishment project, and some, such as distance and sand volume, inform related costs of sand dredging (travel time and distance, amount of sand available) for trade-off analysis in the scenarios (**Section 4**). Again, we note that this framework for determining indicators of borrow area preference can be updated with additional and more detailed geographic information if it becomes available in the future.

Finally, MIDAS users can see where MIMES polygons have a specific grain size (i.e., by grain size ID) and how much of that grain size sand is available by volume in that polygon (**Figure 14**). The MIDAS user interface can also show how each sand type changes over time in each polygon as the model runs forward if such an output is beneficial for the fully parameterized model.

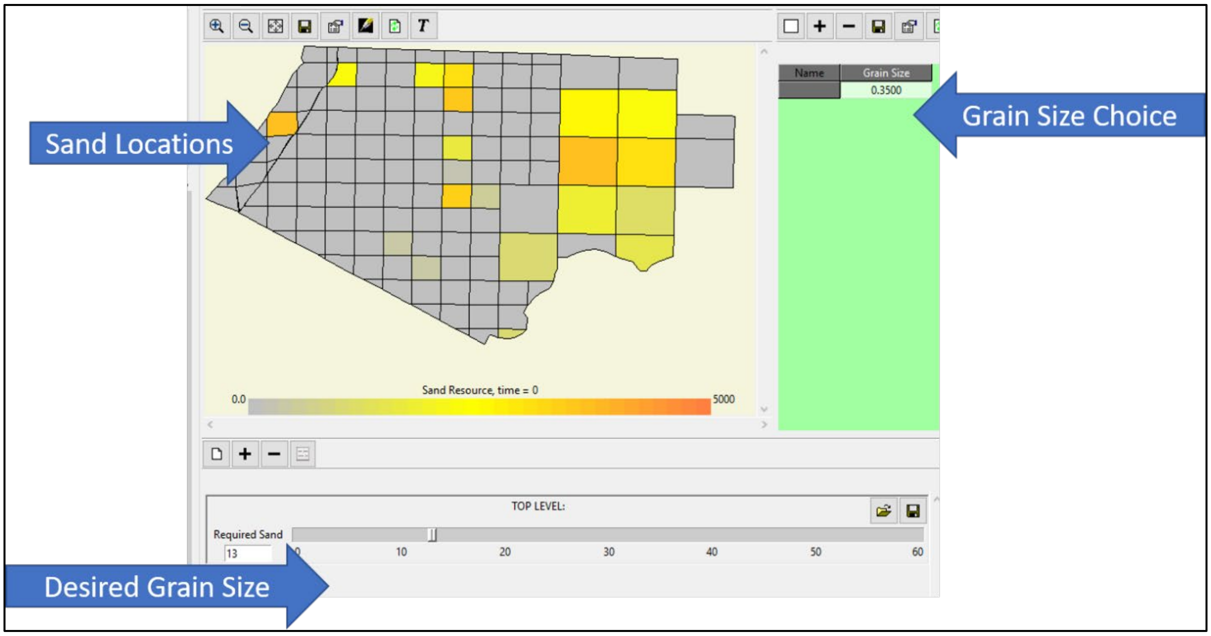


Figure 14. MIDAS user interface illustrates sand locations based on desired grain size.

We further define the sand suitable for sand lance habitat in each marine polygon. Sand lance do not permanently inhabit all available sand and are variable in space and time (Staudinger et al. 2020). In addition, surveys specifically targeting sand lance are limited, and more widespread monitoring (e.g., the NOAA Bottom Trawl Survey) is not viable for gathering sand lance data. Together, this means conclusive spatial data on sand lance distribution at the spatial and temporal scale of our models is lacking. Instead, our models designate all potential habitats that could then be occupied by sand lance using indicators of sand type (grain size), water depth, and potential for planktonic prey alongside the sand lance data that does exist. We also assigned marine polygons a carrying capacity (Staudinger et al. 2020) for maximum sand lance biomass.

4.4 Marine Ecosystem

Our marine ecosystem unit models in each marine polygon are models of intermediate complexity (Plagányi et al. 2014) focused on sand lance. In addition to initial sand lance biomass as an input parameter, the marine unit models also required inputs of sand lance biology and ecology (i.e., how sand lance reproduce, grow, die, and move). First, we trained seasonal patterns of sand lance life history in the model based on the expert opinions of the SBNMS research team and updated these with additional data from the existing literature and field research. Collectively, the unit model of sand lance life history allows sand lance to grow in each marine polygon from eggs to larvae, a proportion to disperse across and from neighboring polygons, and then become adults and age from year to year. The total biomass of sand lance in each marine polygon in each year is calculated as a sum of larvae and adult sand lance (i.e., those at year >1) at the end of that year.

In addition to the life history, both models also reflect essential factors that impact sand lance populations, notably those associated with climate change, such as warming temperatures, predation by other species, and changes in sand habitats precipitated by sand dredging. Temperature is a critical influence on sand lance; in the models, it affects incubation and hatching of eggs, growth, and mortality. Plankton as food is another crucial driver of sand lance, especially the copepod *Calanus finmarchicus*. In marine polygons, plankton changes seasonally as well as from year to year, with populations peaking in late spring and again in the fall. Modeled sand lance forage on the early peak in *Calanus* in MIMES but, in reality, do not actively feed during the fall peak as they are in spawning season. We used the determined feeding peaks to drive a similar dynamic in the model. Also, in the models as in the real world, *Calanus* abundance impacts sand lance via lipid content, which is vital for sand lance growth and for driving dynamics in species that feed on sand lance, as sand lance richer in lipids are more nutritious prey. In the marine unit model, sand lance foraging results in the accumulation of lipid content, which, in turn, has implications on growth, mortality, and biomass available to predators.

Modeled predators of sand lance include four multispecies predator groups and delineate between "resident" and "migratory." Resident species exist in the same polygon as a sand lance population, including the herring and mackerel group and a groundfish species group. All critical for commercial fisheries, these are parameterized as existing and feeding within the unit model of each polygon. Migratory predators are whales and seabird groups and are not modeled in a specific polygon but are attracted to a polygon with sand lance. They begin feeding once the abundance of the sand lance in a polygon exceeds a threshold. All predator groups are governed by "predation rules" that set what age classes of sand lance the predators feed on and when during the year they feed and if they feed on sand lance in the water column, on the bottom, or at the surface. The model itself is not three-dimensional (i.e., it does not have a bottom, mid-water, or surface delineation) but the last predator distinction informs whether the predator can access sand lance when they are "resting" in the bottom over winter. These rules result in predation dynamics in the model, which impact sand lance biomass.

Unit models in each marine polygon also communicate with one another in the MIMES spatial model via sand lance dispersal. Sand lance most often disperse as larvae, moving much less once they recruit as adults (Staudinger et al. 2020). Larval dispersal is an essential biological driver of the model's sand lance population dynamics across space and time. However, how ocean currents move larvae across an area is a stochastic process that would require additional and complicated current models attached to MIMES. Without this, we instructed the model to stochastically choose daily directions for a proportion of larvae from each MIMES polygon to "disperse" to neighboring polygons. Research also demonstrates the importance of dispersal from areas outside our study location, allowing input of new sand lance larvae from locations outside the model arena.

4.5 Sand Mining

Sand dredging and beach renourishment is another way the unit models in each polygon connect in the fully implemented spatial MIMES and is the main communication channel between the upland and marine polygons in both NJ-MIMES and SB-MIMES. For upland polygons needing beach renourishment, the model first initiates sand dredging for the polygon with the highest urgency (see "Coastal Communities," above). Once started, the first step in sand dredging for this polygon is a waiting period of 365 days, which reflects a period for project approval and execution based on real-world estimates. Following this, the model assesses sand demand for the polygon against marine polygons with available sand resources and is open to sand dredging (see "Marine Sand Shoals"). The model selects the one closest to the upland polygon needing renourishment for dredging, and the dredge leaves the coast and travels to the marine polygon at a set sailing speed and mines sand at a set dredging speed. Dredging is restricted to taking 20 cm of sand per pass on an area, which it does until the hull is filled, or the area is depleted of sand, and then the vessel returns to the beach to renourish the beach. This occurs until sand dredging has added enough sand to bring the upland polygon back to its preferred sand volume (see "Coastal Communities"). Once completed, sand dredging is evaluated in the model based on operation efficiency, which is the amount of sand added to a beach per hour spent traveling and dredging per day.

Sand dredging also connects across marine and upland polygons via impacts on sand lance, which we model as direct and indirect impacts. Direct impacts include additional mortality to sand lance in the marine polygon where sand dredging occurs. Indirectly, sand dredging reduces the volume of sand in a polygon, and thus the habitat available, adjusted in the model via the polygon's carrying capacity for the sand lance. An additional indirect impact of sand dredging is the related sand plumes that result, extending across a much wider area than the sand resource itself, depending on sand grain size and other conditions (Wenger et al. 2017). Therefore, we also include an indirect impact on sand lance via resulting turbidity. Collectively, these impacts also have indirect outcomes for sand lance predators by potentially reducing the biomass of sand lance available for them to eat. This could have further consequences for commercial and recreational fisheries, whale watching opportunities, or the efficacy of laws protecting certain species of marine mammals and birds (Moore et al. 2009; Valdivia et al. 2019).

4.6 Designation of Sand Lance Habitats

It is important to carefully ascertain with data what constitutes critical sand lance habitats that we then reflect in both NJ-MIMES and SB-MIMES—that is, the same elements determine sand lance “hot spots” in reality and in the models. Initially, we hypothesized this would be a combination of sand grain size and water depth and aligned with areas of high food for sand lance, in this case zooplankton and *Calanus finmarchicus*, a key lipid-rich plankton species. We also know from field experience and discussions with our research team that physical characteristics, such as upwelling and oceanographic currents, are also important, but they are outside the scope of this contract; we aimed to find hot spot proxies from the data at hand and avoid involved oceanographic modeling. To evaluate our hypotheses and determine what characterizes sand lance habitat, we wanted to include as much information as possible, so we did not limit this analysis to our study locations and instead looked across the entire seaboard from the Gulf of Maine to New Jersey where useful data could be found. We reasonably assumed any relationships found between sand lance and habitat across the region would be the same for our study locations, and this wide lens was necessary given the paucity of data in regions beyond SBNMS.

For this assessment, we started by evaluating locations where NMFS trawl surveys found sand lance shown in **Figure 15**. Within the trawl data from 2013–2017, 88 of 2,319 trawls captured sand lance. We overlaid these survey locations with GIS maps of depth and information on the substrate and sand grain size from the TNC data (**Table 1**). These sand lance locations had a mean depth of 61.6 m (± 48.5), with 89% (78 of 88) of the NMFS trawls with sand lance also occurring within the 100-m isobath. We extracted sand content and grain size data from 88 sand lance locations. We found sand lance occurred over the substrate with 71.1% (± 22.7) sand content of relatively coarse grain sizes (0.435 mm ± 0.387), and 78% (56 of 78) were found over substrates with > 50% sand and grain sizes in the range of 0.35–2 mm, which is considered as very fine to fine gravel (Krumbein and Sloss 1963).

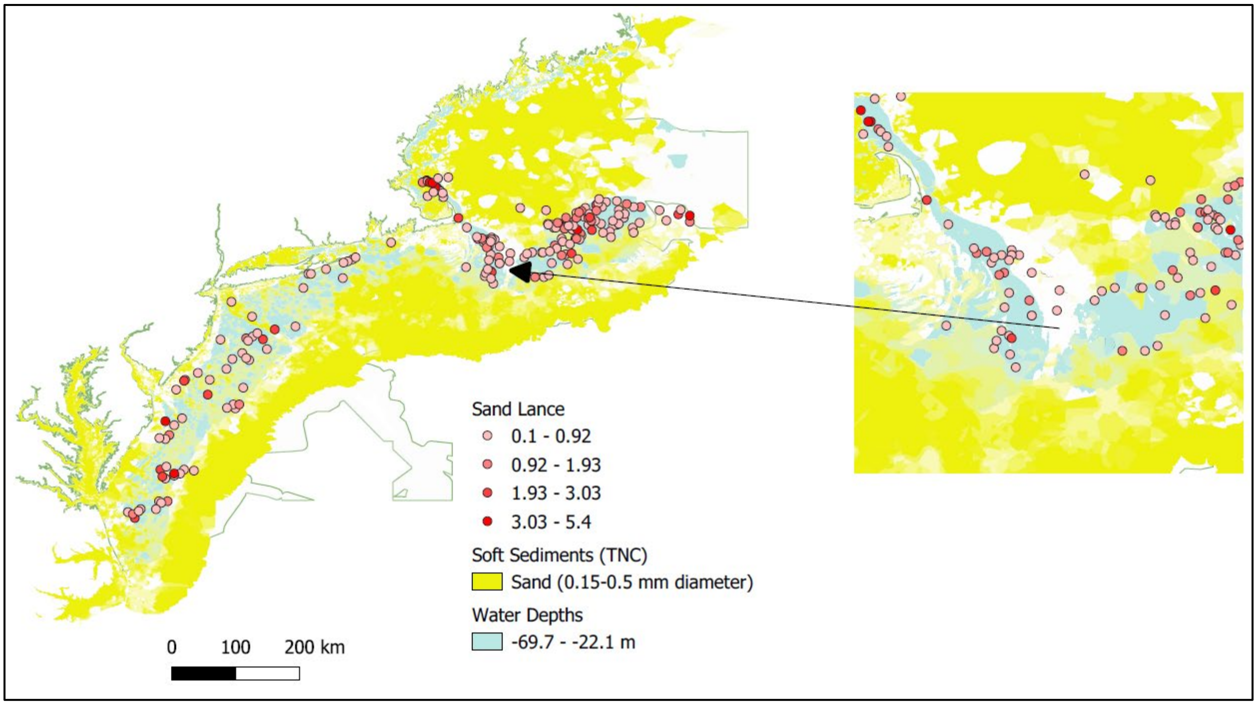


Figure 15. Survey locations of sand lance catches in previous research.
Catch is shown as red circles, with increasing saturation indicating a greater concentration of sand lance; values are in log10 kg of sampled biomass over depth (light blue) and substrate (yellow).

We also aimed to connect the physical characteristics of sand lance habitat with biological ones (i.e., locations of important sand lance food). Sand lance feeds on zooplankton, and for NJ-MIMES we used EcoMon data on plankton from 1977 to 2015 (McClatchie et al. 2014). From this data, we averaged zooplankton biomass in ml/m^2 per month over the entire period of the data (1977–2015) for each NJ-MIMES marine polygon to determine the spatial distribution of plankton across the NJ marine area. For those areas without EcoMon data, we used an average from the surrounding eight polygons.

We overlaid our resulting maps against sand lance locations from the NMFS surveys. We compared areas of zooplankton with potentially suitable sand lance habitat based on sand characteristics (depth, type, and size of sand). Based on real data, we hoped to use these variables collectively to delineate sand lance "hot spots" in the model. Instead, we found areas of high sand lance in the model did not correspond with either high zooplankton or appropriate sand as expected (**Figure 15**). The left panel of **Figure 16** shows the MIMES extrapolated distribution of zooplankton in NJ-MIMES polygons. The map displays areas of sand lance suitability in red, with increasing saturation denoting more zooplankton. Locations marked as triangles on the same map indicate the survey locations of the sand lance; open circles indicate locations where the survey did not find sand lance. The right panel shows the locations of potentially high-quality sand for sand lance denoted in orange, with increasing saturation indicating increasing sand quality. The blue circles highlight some areas where prior surveys found sand lance that do not overlap with high zooplankton or sand quality (shade of blue denotes corresponding polygons in both panels). SB-MIMES was constructed similar to NJ-MIMES.

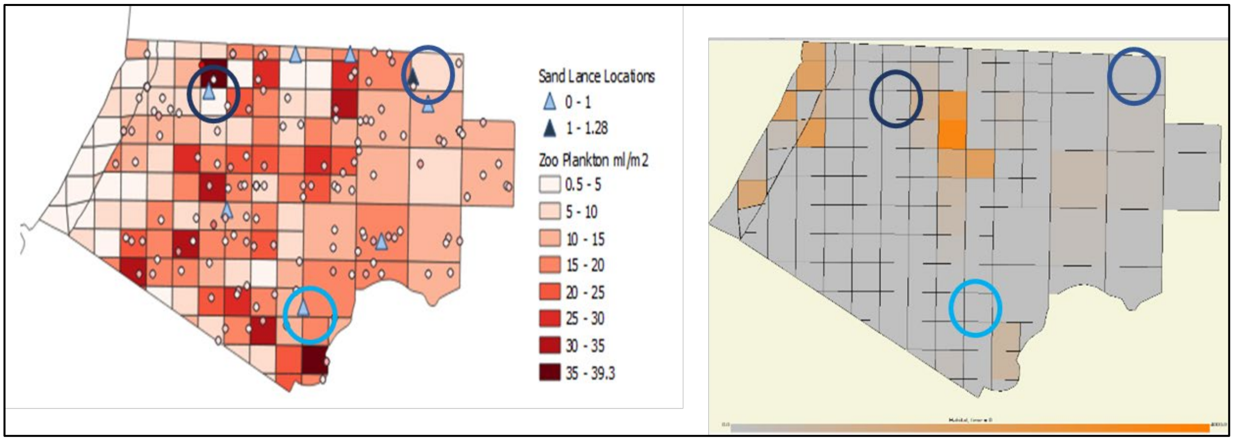


Figure 16. Determining sand lance "hot spots" in the model from data.
The blue circles highlight some of the areas where sand lance was found in surveys that do not overlap with high zooplankton in MIMES.

In addition to characterizing sand lance habitat in our marine unit models, we also determined sand lance biology and ecology for the unit models (i.e., how sand lance reproduce, grow, die, and move in the model modeled using *Equations 3-9* in **Appendix A**). We first developed a Leslie matrix (Jensen 1974) in MIMES for a life history to drive the sand lance population across its different growth stages. We modeled how sand lance grow from eggs into larvae, recruit into the spawning population, and grow from day to day and then from year to year.

Sand lance mortality in MIMES includes age-specific predation rate. The mortality due to winter temperatures of the ocean bottom (SBT) was documented by Staudinger et al. (2020) and is of importance when considering the effects of climate change on seawater temperatures. The model derives sea bottom temperatures from sea surface temperatures and depth. As depths increase, temperatures decrease to a minimum of 4°C when water is at its highest density. When formulated this way, winter mortalities are more prone to occur in shallow water and set the upper depth boundaries for sand lance population establishment. The model assumes that dredging mortality is a percentage of the total sand lance population when dredging occurs in an area. Due to the lack of information, the model does not consider this mortality proportional to the dredging effort.

We choose predated biomass to be an indicator of the contribution by the sand lance to commercial fisheries and conservation interests. Predation of the sand lance by herring, mackerel, and groundfish is essential to commercial fishing, while predation by whales and shearwaters contributes to conservation. The locations of the sand lance predation are situated in Massachusetts, mainly along the eastern slope of the sandbanks within the SBNMS. In New Jersey, the sand lance predation contributions are assumed to follow a “stepping stone” (or zigzag) pattern. These sandbanks spanning from east to west serve as a recolonizing habitat in good years after the loss of populations in the bad years. Impacts on the patches of habitat influenced the recolonization process. Adding the predator population dynamics prepares the model for an opportunity to couple these sand lance dynamics with a more complex food web model and interaction with ocean management (Altman et al. 2014). **Appendix A** (Section A.4) describes MIMES parameter settings for predation.

The expertise of the SBNMS research team and their parallel work on this project further informed our modeling. The research team developed a “vulnerability matrix” (**Figure 17**), with a 0–5 ranking of the vulnerability of sand lance to sand dredging at different life history and other stages and in each month of the year. The team similarly considered vulnerability for other species in sand habitats, specifically whales, seabirds, and commercially targeted fishes. The resulting matrix allowed the team to assess what times of year sand lance and dependent species may collectively be most vulnerable, determining August through September to be the period of least risk for sand dredging impacts. This demarcated period does not mean that there are no potential impacts to sand lance or indirectly for other species, but that those risks are relatively less than other times of the year.

Activity	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Rank calculation notes
SL spawning	0	0	0	0	0	0	0	0	0	4	5	4	Ranks based on data and observations during research cruises - not developed quantitatively / systematically
SL daily bottom time	3	3	3	3	3	3	4	5	5	5	5	4	Ranks are scaled (not quantitatively / systematically) by how much time fish spend in / near sand in a 24 hour period
SL settlement	0	1	4	5	5	4	0	0	0	0	0	0	Ranks based on otolith data and observations during research cruises - not developed quantitatively / systematically
SL eggs	5	5	3	2	0	0	0	0	0	0	5	5	Ranks based on lab rearing studies and observations of larval sand lance during research cruises - not developed quantitatively / systematically
SL foraging	4	5	5	5	4	3	3	1	1	1	2	3	Ranks based on stomach content analysis - not developed quantitatively / systematically
SL survivorship (lipids)	5	5	5	4	3	2	1	1	1	1	5	5	Ranks based on stomach content and lipid analysis - not developed quantitatively / systematically
SL reproductive success (lipids)	2	4	5	5	5	5	4	1	1	1	1	2	Ranks based on stomach content and lipid analysis - not developed quantitatively / systematically

Figure 17. Dynamic patterns of sand lance lift history from the vulnerability matrix, shown over the course of a one-year simulation in MIMES unit model.

As noted earlier, summarizing the wide-ranging science outcomes provided by the expert vulnerability matrix was valuable for translating this information to help define the Leslie matrix (Leslie 1948) for sand lance life history used in MIMES. **Figure 18** shows the dynamic patterns of sand lance life history from the vulnerability matrix, demonstrated over a 1-year simulation in the MIMES unit model. In addition, it remains vital to continue to delineate risks while considering the changing landscape of coastal communities and outcomes for people that precipitate new trade-offs relevant for BOEM. To this end, the operationalization of the vulnerability matrix within MIMES allows us to explore how emerging effects evolve in time, differ across space, and interact with additional consequences for human communities. Even with just one species studied here (*A. dubius*), it is apparent that there are different effects and, therefore trade-offs, depending on the timing and location of dredging.

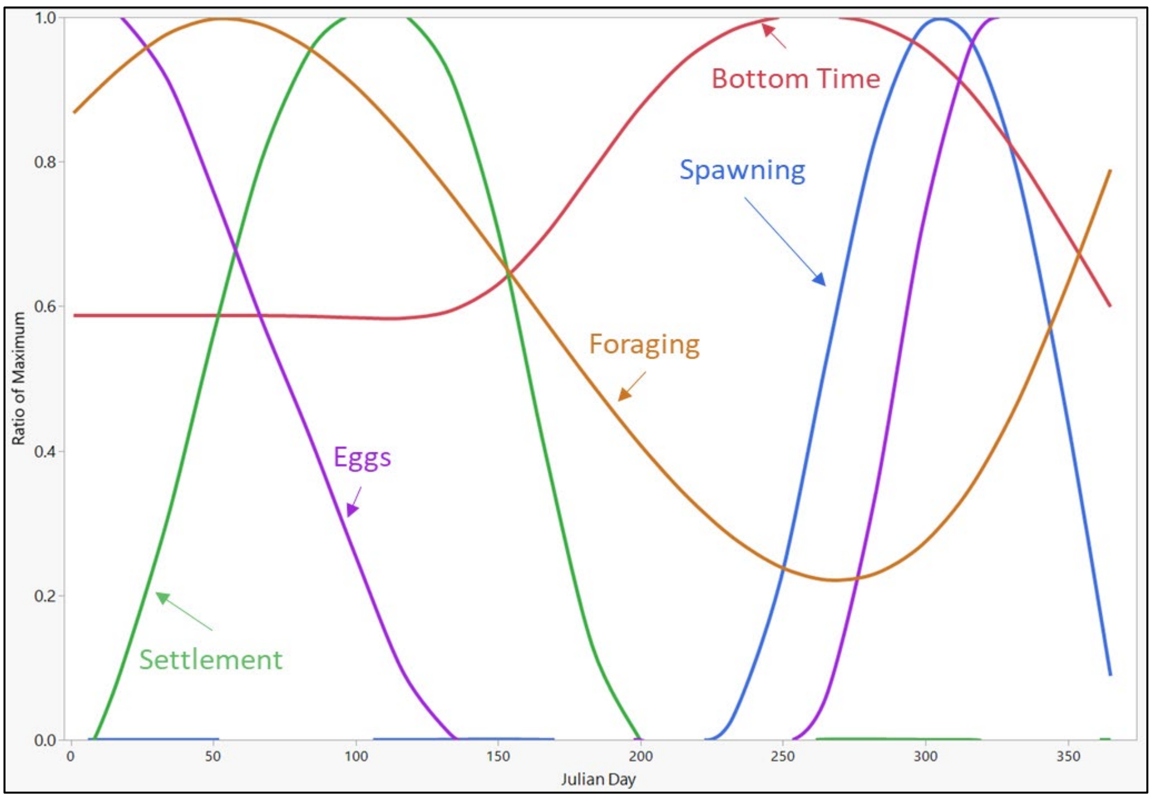


Figure 18. Dynamic patterns of sand lance life history from the vulnerability matrix, shown over the course of a 1-year simulation in the MIMES unit model.
MIMES model of sand lance life history. The x-axis shows time (Julien Day), while the Y-axis shows the probability of sand lance dynamics.

To summarize, our discussion with the experts (**Figure 4**) related to sand lance is captured in modeling MIMES.

- Sand lance occupy a wide range of environmental conditions.
- Sand lance appear to be dormant predominantly in winter; spawning usually occurs in fall or winter (the two species of our study area), eggs are demersal, and larvae may hatch at times of low food abundance.

- Sand lance spend much of their time buried in specific substrates.
- Copepods are the primary food of sand lance.
- Sand lance life stages and the distinction between *A. americanus* and *A. dubius* are important for this BOEM study.
- Sand lance migrate to deeper waters in winter and are rarely caught in the water column during the winter months. They appear to remain inactive or in hibernation while buried in intertidal and shallow subtidal substrates. American sand lance can be found within the intertidal, but below the current waterline, at any given time. Northern sand lance are to our knowledge never in the littoral zone, or at least not for long. Temperature is a limiting factor at all depths if the water stays above 10°C while sand lance are inactive in the sand.
- Sand lance are abundant in preferred habitats from spring to late summer and uncommon during early summer; adult sand lance (mostly second year) are the most abundant of early winter-spawning species.
- Later in the summer, juveniles become the most numerous age class as they migrate inshore and recruit to nearshore populations. Older fish may disappear early in summer. Age of maturity of *A. dubius* ranges between 2 years (northern population) to 3 years (southern population) in the Northeast US (Nelson and Ross 1991; Staudinger et al. 2020, Winters 1983).
- Sand lance are important prey for over 100 species of consumers, including 40 species of birds, 12 species of marine mammals, 45 species of fishes (including many of commercial importance, e.g., flatfishes), and some squid species.

5 MIMES Model Outputs—Scenarios

The next step for decision support is to take the prior empirical science and integrate it to develop scenarios of what might happen given different impacts or decisions now—so what are outcomes or trade-offs that could arise due to various decisions?

MIMES enables us to do scenario modeling. The goal of our MIMES work is to provide science-based decision support, namely on the risks of sand dredging on the sand lance and related, indirect effects to sand lance predators, and corresponding human values and services.

5.1 Scenario Creation

The time considered in each MIMES scenario is from 1977 to 2100. We use the prior 73 years for MIMES validation (back to 1977) and use the next 30 years for prediction (up to 2050). The model runs in daily time stamps. Our visualization typically hides past years (before 2015) from displaying. In each scenario, sand lance (both *A. dubius* & A. *americanus* as trawl data does not differentiate between species) dynamics is the primary focus for species modeling in MIMES. Broad levers are examined, such as restrictions on sand dredging, restricted areas, climate change conditions, and sand dredging cost/demand.

To evaluate scenario outcomes, we start with a reference scenario and compare results with an additional scenario (i.e., a counterfactual) (Fulton et al. 2015). **Figure 19** shows the scenario trade-offs. This approach allows a more detailed assessment of changing costs and trade-offs via comparing indicators that are the same across all scenarios and with all other aspects of the model approach kept the same. This latter point also means that any uncertainty in outcomes based on the model is the same across all scenarios, reducing the potential for spurious effects based on model assumptions or uncertainty.

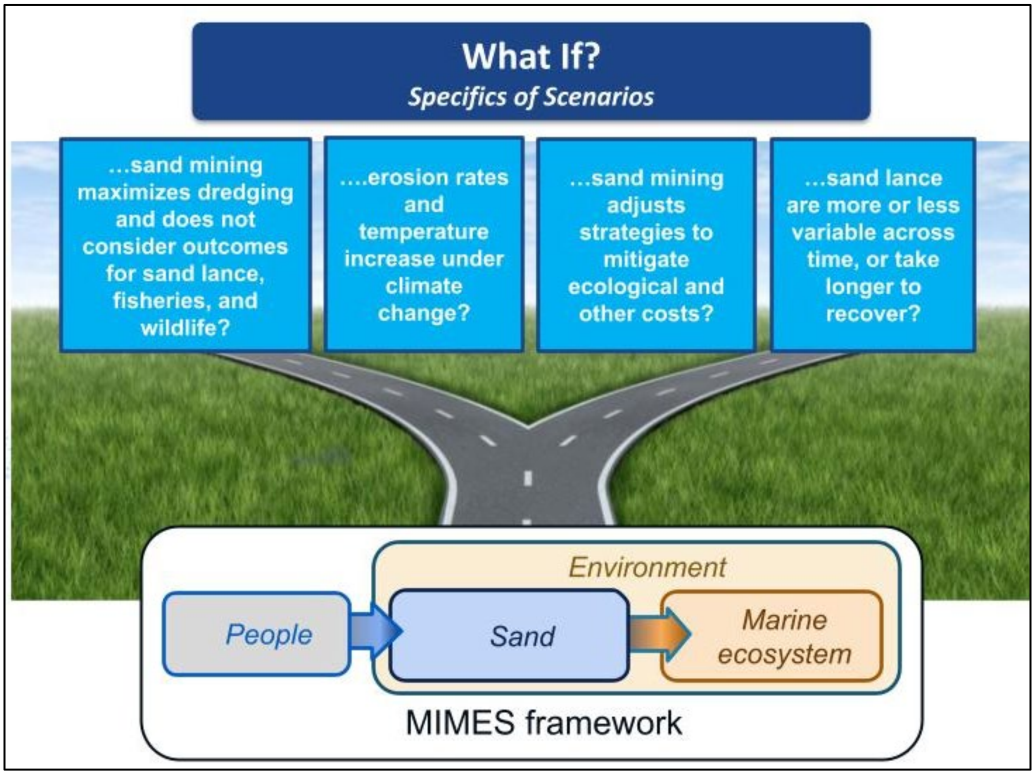


Figure 19. MIMES "what if" scenarios addressing sand mining, sand lance, and ecological variables.

In our reference scenario, all sand resources in marine polygons are off-limits to sand dredging in Federal waters (e.g., the parameter called "taboo" is set at 1 for all polygons more than 3 nm offshore). We then compare this with a mining scenario, which allows sand dredging to occur in these areas, fulfilling beach renourishment requirements as soon as they arise, and industry needs, e.g., reducing travel and fuel costs by going to the closest borrow areas.

Finally, we specifically leverage uncertainty to probe how outcomes change with resulting differences in the ecosystem. As with all models, there are multiple sources of and different types of uncertainty (Link et al. 2012). Here, we first considered how those sources would manifest in model outcomes and then how those differences may relate to actual changes in the ecosystem, currently and in the future. For example, there are several areas where data is lacking on relationships and parameters in the life history of sand lance—but ultimately, to our ends here, these result in more or less sand lance in the model. Variation in the amount of sand lance is useful for bracketing our uncertainty in model outcomes. We can reasonably assume sand lance populations will be variable in the future of climate change. More details on this approach are in **Appendix A**.

The comparison enables for a clear assessment of changing costs and trade-offs, i.e., the same type of costs is determined for each scenario run in the model. Further, the same outcomes (economic, ecological, and other costs and trade-offs) are compared, holding constant all other aspects of the model. This latter point means that any uncertainty in outcomes based on the model is maintained across all scenarios, allowing us to focus on differences between scenarios (i.e., how our additional scenarios change outcomes, not how model assumptions or uncertainty change outcomes). We note that the flexibility of MIMES means a multitude of scenarios is possible; we only consider a few here. **Figure 20** shows the flow chart of MIMES and display in MIDAS of potential scenarios and outcomes.

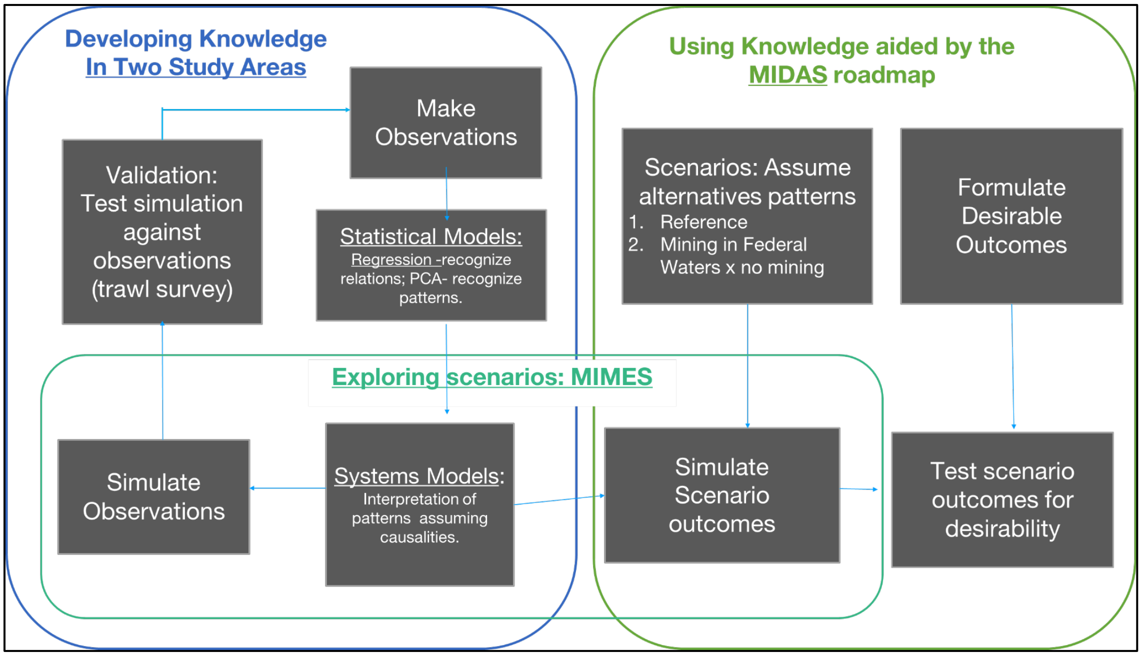


Figure 20. MIMES-MIDAS model and scenario visualization.

5.2 Comparing Scenarios

To compare scenarios, we consider the same indicators for people, the sand dredging industry, and the ecosystem (**Figure 17**) to conduct a trade-off analysis. We measure these indicators at the end of the model run for overall differences between scenarios, at different intervals within the model run, or as movies and maps to see indicators over time as the model runs. We can build scenarios to display a road map of possible decisions, impacts, and outcomes to explore trade-offs for guiding decisions, as shown in **Figure 18** and **Figure 20**. We ask "what if?" questions to see possible outcomes. This exercise is not prescriptive advice but a road map of what BOEM can use to see different effects of decisions in various scenarios and other potential future impacts. For example, what are the risks to commercial fisheries and wildlife if sand dredging only concerns itself with minimizing time at sea and maximizing dredging? Will climate change exacerbate these risks? Can sand dredging reduce risks by shifting locations, limiting how much sand can be taken from an individual shoal, or delaying dredging to certain times of the year or when ocean temperatures are high? What are the associated trade-offs for the industry of changing strategies to make these concessions? How do these change as we alter aspects of the model, we are less certain about—such as how variable sand lance are from shoal to shoal or how long it takes them to recover?

5.3 Reference and Alternative Scenarios

Reference Scenario: The reference scenarios represent the system experiencing no climate change. MIMES reference scenario model is built with drivers (e.g., zooplankton/*Calanus spp.,* sea surface temperatures, and erosion rate dynamics). The system is in a steady state with no climate change. This assumption is unrealistic as we know drivers will be altered by climate change, but this scenario is needed for comparison with other scenarios. The scenarios as described will compound for those used—i.e., we will need a Reference and a Mining scenario, but also Reference x Climate Change A scenario, etc. There is also 'abundant' sand (2 m depth), and sand dredging is restricted to state waters (denoted as TabooFW).

“Mining” Scenario: MIMES with all the same as above (constant drivers, abundant sand), but dredging is allowed in all marine polygons, i.e., all Federal waters are open.

Limited Sand Scenario: There are no data on sand depth and, therefore, the volume of sand available. Sand depth is reduced to 1 m. This allows us to explore how results change if sand is a limiting factor.

Overlapping Scenario: Sand lance and sand dredging occur in the same sand grain size and overlap in water depth. This assumption may not be realistic (e.g., if sand dredging evolves to deeper depths than is currently feasible). But there is uncertainty in our understanding concerning the overlap of sand dredging and sand lance, which has implications for results. Even if it is unrealistic, running a scenario that ensures overlap is still helpful to see how the model may play out. In MIMES simulations, overlapping via water depth is noted as “100 m”.

High and Low Sand Lance Scenarios: The uncertainty in knowledge and data on the sand lance and their biology means there is uncertainty in how much sand lance is in the model. We are testing out MIMES model results with more and less sand lance model this uncertainty.

Development of the scenarios is documented in **Appendix A (***Equations 17–21***)**.

5.4 Climate Change Scenarios

Under the Climate Change A scenario, the average availability of the zooplankton *Calanus spp.* declines over time, and sea surface temperatures are rising. *Calanus spp.* is the preferred feed for sand lance due to its high oil content and thrives better in cold waters. Higher sea surface temperatures negatively impact sand lance as temperatures at the ocean bottom in the winter are lethal when the sand lance is buried. Under the Climate Change B scenario, we assume faster short-term erosion rates and slower accretion rates, as Hapke (2010) reported.

Each of the scenarios makes several assumptions of sand availability. Sand deposits of 2 m deep represent abundant sand resources, deposits of 1 m deep represent limited sand resources. For management decisions, we consider where sand dredging is permitted, either everywhere (Taboo=Taboo0) or restricted to state waters (Taboo=TabooFW). Many other potential effects of climate change are not included in this report and can be explored in future studies.

5.6 MIMES Simulations for Scenarios

Table 3 indicates scenario name, time stamp, scenario indicators such as sand, dredging, and future climate change. Color for future runs denotes priority, higher priority in a darker shade.

Table 3. MIMES scenarios and indicators

Scenario / Model Run	**Past or Future**	**Sand**	**Mining**	**Future Climate Change**
Past State Mining	*Past*	*Abundant (2 m)*	*State waters only*	*No*
Past Reference Mining	*Past*	*Abundant*	*All Federal waters open to dredging*	*No*
Past Directed Mining	*Past*	*Abundant*	*Only one polygon open to dredging (51)*	*No*
Reference System	Future	Abundant	All waters open for dredging	No
Mining Restrictions	Future	Abundant	All Federal waters closed to dredging	No
Reference + Limited Sand	Future	Limited (< 2 m)	All waters open for dredging	No
Mining Restrictions + Limited Sand	Future	Limited	All Federal waters closed to dredging	No
Reference + Climate Change A	Future	Abundant	All waters open for dredging	Yes—plankton and temp
Mining Restrictions + Climate Change A	Future	Abundant	All Federal waters closed to dredging	Yes—plankton and temp
Reference + Climate Change A + Limited Sand	Future	Limited	All waters open for dredging	Yes—plankton and temp
Mining Restrictions + Climate Change A + Limited Sand	Future	Limited	All Federal waters closed to dredging	Yes—plankton and temp
Reference + Climate Change B	Future	Abundant	State waters only	Yes—erosion rates
Mining + Climate Change B	Future	Abundant	All Federal waters open to dredging	Yes—erosion rates
Reference + Climate Change B + Limited Sand	Future	Limited	State waters only	Yes—erosion rates
Mining + Climate Change B + Limited Sand	Future	Limited	All Federal waters open to dredging	Yes—erosion rates
Exploration 2: Overlapping Sand Lance And Dredging	Future	Abundant	All Federal waters open to dredging	No
Exploration 3: Sand Lance Abundance	Future	*Abundant*	All Federal waters open to dredging	No
Restricted Mining	Future	Abundant	Restrict sand dredging as per Update 3	No
Restricted Mining + Climate Change A or B	Future	Abundant	Restrict sand dredging as per Update 3	Yes—plankton/temp **OR** erosion rates
Directed Mining	*Future*	*Abundant*	*Only one polygon open to dredging (51)*	*No*

6 Results and Discussion

We ran one scenario in MIMES to simulate 73 years at daily intervals for results presented here. Due to stochasticity in input variables, we ran each scenario six times in MIMES. The MIMES model outputs are aggregated to monthly (daily) values. MIDAS visualization shows the average of six simulations. MIDAS visualization can display the effects of dredging restrictions on ecological costs against the outcomes for people (reduction in sand deficit) and sand dredging (lowest prices in terms of time and distance traveled to complete projects). We can then compare these outcomes under different management scenarios.

MIMES/MIDAS Scenarios analyzed using indicators are shown in **Figure 21.**

Scenario	Measure/Indicator	Dimensions	Purpose / Description
Reference System	Average Biomass of Sandlance (tonnes)	By Month, By Year, By Marine Polygon	To show Map of Total Sandlance Biomass highlighting each polygon value
	Count of Sandlance Locations (units: number of days)	By Month, By Year, By Marine Polygon	Show where the sandlance is over time
	Sum of Days where Beach Sand is Below Threshold ("Beach Exposure Risk") (units: # of Days)	By Month, By Year, By Beach Polygon	Explain Beach Risk monthly over time
	Average Dredging Expenditure (cubic meters sand / day)	By Month, By Year, By Beach Polygon	Show cost of dredging over time
Mining Restrictions	Average Biomass of Sandlance (tonnes)	By Month, By Year, By Marine Polygon	To show Map of Total Sandlance Biomass highlighting each polygon value
	Count of Sandlance Locations (units: number of days)	By Month, By Year, By Marine Polygon	Show where the sandlance is over time
	Sum of Days where Beach Sand is Below Threshold ("Beach Exposure Risk") (units: # of Days)	By Month, By Year, By Beach Polygon	Explain Beach Risk monthly over time
	Average Dredging Expenditure (cents^3)	By Month, By Year, By Beach Polygon	Show cost of dredging over time

Figure 21. MIMES/MIDAS scenario analysis outputs and run configurations.

The various indicators can be filtered by spatial and temporal dimensions and displayed in MIDAS. Choice of model outputs as well as model runs can be compared under the MIDAS system as shown in **Figure 22**.

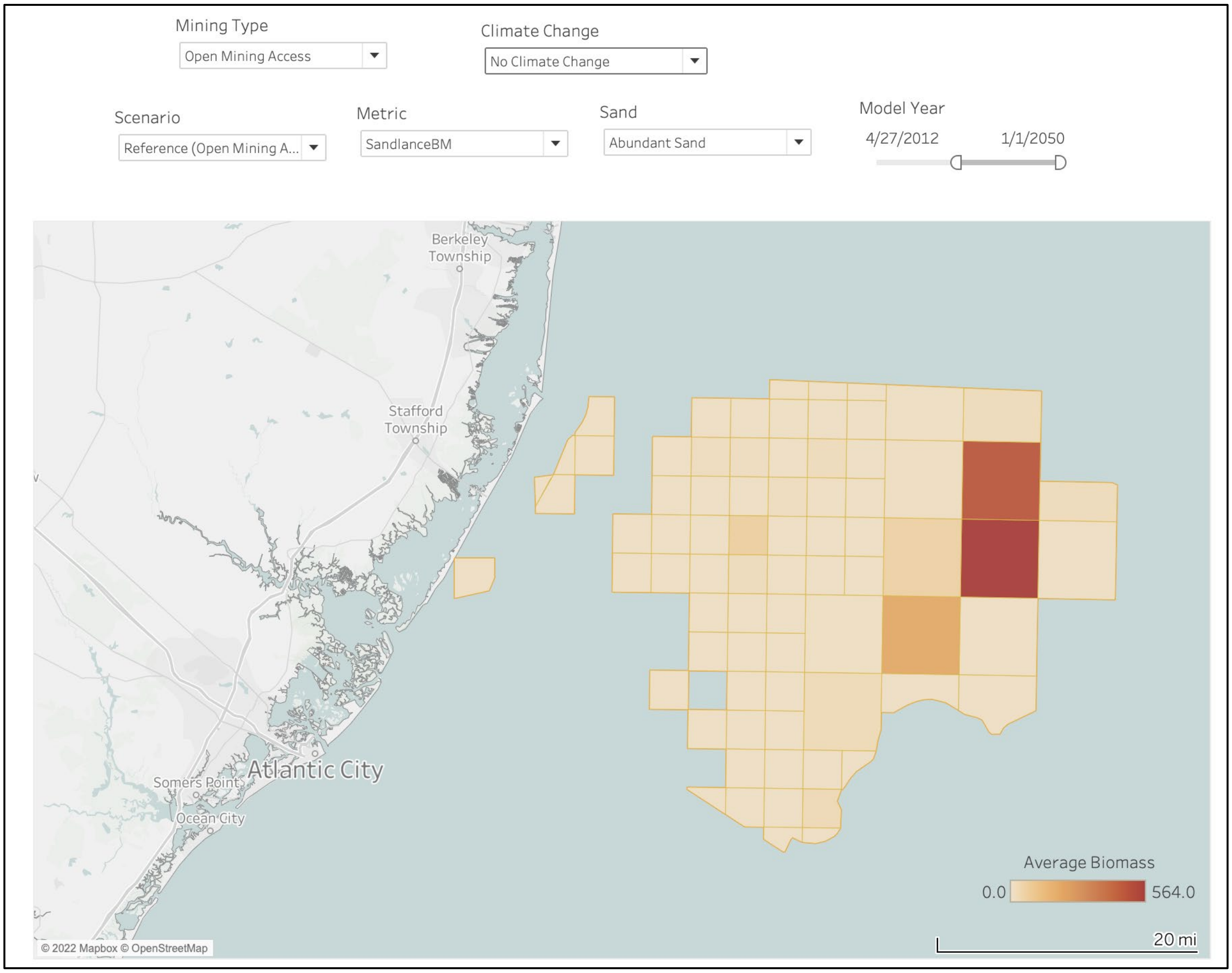


Figure 22. MIDAS model scenario visualization illustrating user-defined model inputs and runs.

6.1 Ecosystem Indicators

MIMES is primed to produce many indicator outputs. We describe the analysis and results of these simulations.

6.1.1 Sand Lance Biomass

The time considered in each MIMES scenario is from 1977 to 2100. We use a total of 73 years for MIMES. We validate the model going back to 1977 and use the next 30 years (2020–2050) for a forward prediction. The effects of sand dredging from 2015–2050 are simulated, and sand lance biomass is visualized under two NJ-MIMES scenarios.

Figure 23 shows the fluctuations in sand lance biomass simulated over a 73-year period assuming 4 different scenarios for both of our study sites. The scenarios explore assumptions on climate change and management responses. Under the climate change scenario, we assume beaches will experience increased erosion (See Equation 1-2 and A-5 in **Appendix A**), and that ocean water temperatures (See Equation 1-2 in **Appendix A**) will increase. Increased temperatures cause sand lance mortality during the winter and a decline in *Calanus*, the major sand lance food source. The management response assumes restricted access to Federal waters. Four scenario simulation results of normalized sand lance biomass are shown in

Figure 23: 1) no dredging in Federal waters assuming no climate change (blue), 2) no dredging in Federal waters assuming climate change (red), 3) dredging assuming no climate change (green), and 4) dredging assuming climate change (purple). The NJ-MIMES shows consistently higher biomass values under No dredging restrictions assuming no climate change (green), a curious result that bears further exploration. Limiting dredging to state waters depleted much of the sand lance populations in those areas. Opening Federal waters for dredging diverts some of this impact to areas where the impact has less effect on sand lance. NJ-MIMES shows that after 40 years, the amount of sand dredged per day draws 5–10K cubic yards, which would not be sustainable. From the model results, we can conclude that dredging for beach nourishment under all scenarios will run out of sand resources fairly quickly to render dredging financially viable with no real differences among the scenarios.

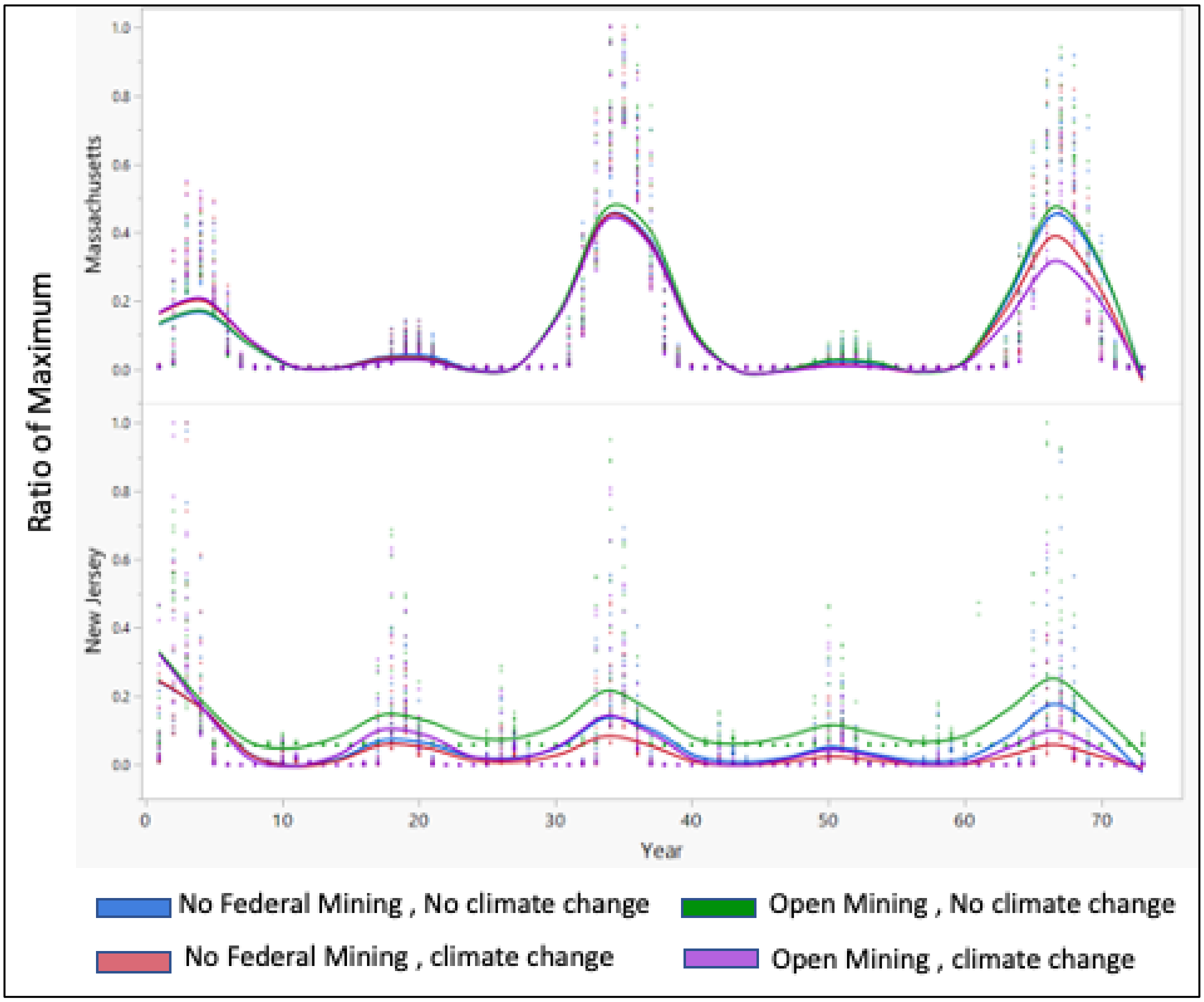


Figure 23. Effects of limited and restricted mining in model scenario visualization in MIMES.
The legend spells out the scenarios (the same four executed for New Jersey and Massachusetts), The points are the averages of scenario outputs from six simulations running the same scenario. (Each scenario is represented by 73 years times 12 months, a total of 876 data points.) The trend lines summarize the running averages generated in jmp. Normalized sand lance biomass is represented on the vertical axis.

Note that dredging occurs in the same areas that sand lance prefer due to the correspondence in sand grain size and other characteristics although they may be spatially separated due to different depth conditions. **Figure 24** displays the average distribution of sand lance biomass in New Jersey in NJ-MIMES. The map shows the highly productive zones in the study area where larvae enter the north (by model definition), signifying the ephemeral nature of sand lance in these waters as most of the biomass is imported and not produced in the area. **Figure 25** shows the nearshore areas with a less pronounced presence of sand lance. These areas could be harboring mostly *A. americanus* as opposed to *A. dubius,* based on data gathered on depth distribution of the two species, so that the impact of dredging would mostly involve *A. americanus* but possibly both species.

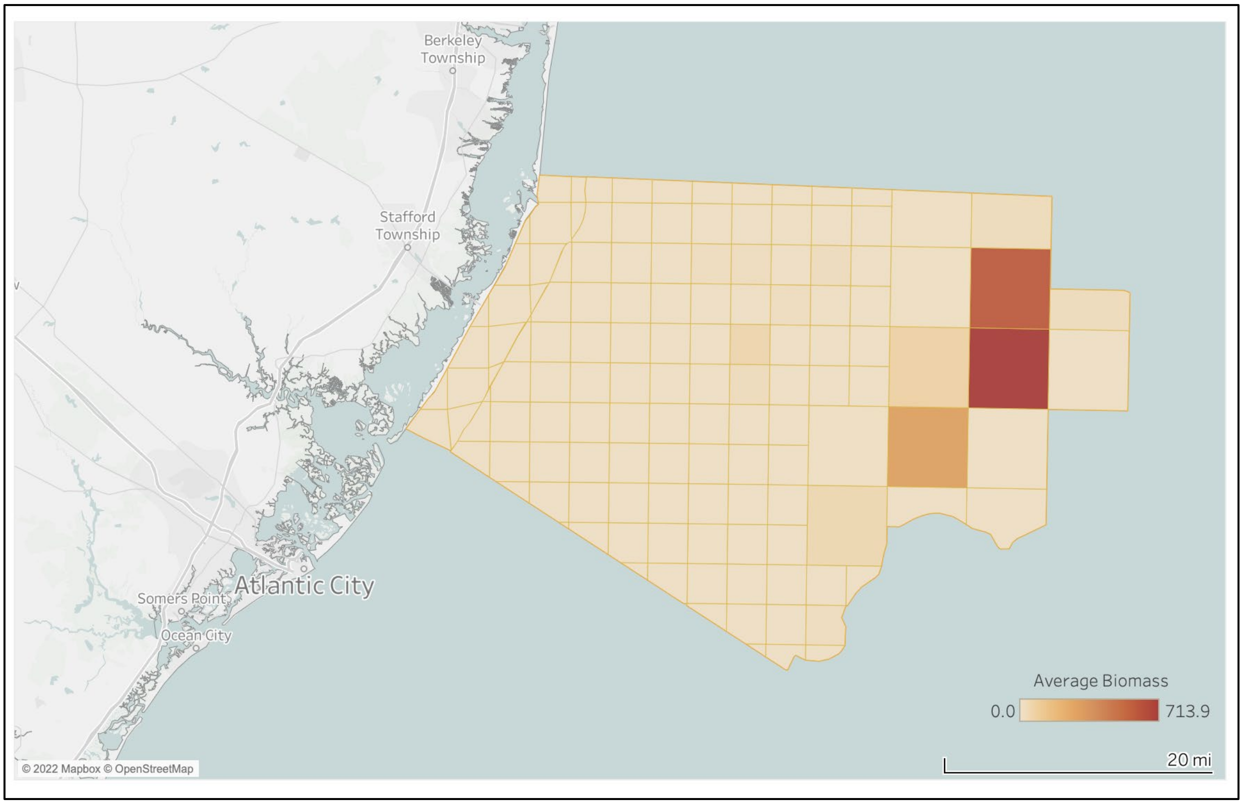


Figure 24. Sand lance biomass model scenario visualization in NJ-MIMES.
MIDAS displays the biomass values in each cell over the 73-year time period.

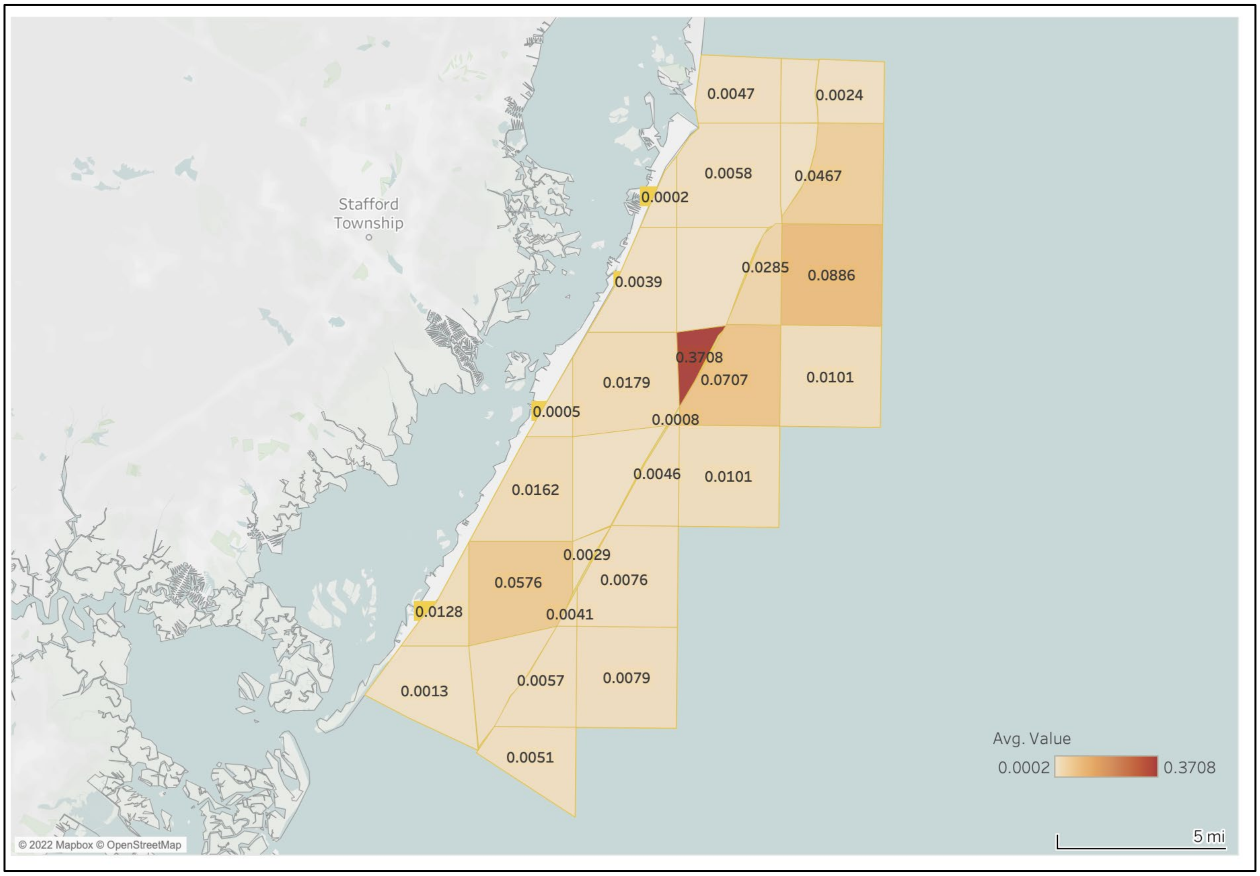


Figure 25. Sand lance biomass model scenario visualization in NJ-MIMES.
Each marine polygon records a value at each point in time in each scenario.

6.1.2 Predated Sand Lance Biomass

MIMES models predated sand lance biomass as a proxy indicator for predatory species (based on commercial fishing, whale watching, and seabirds) data. MIDAS can display the final total sand lance biomass predated by predator group by polygons and years. We added these data layers and estimated the total sand lance biomass predated by predator group by polygon and year. Predated biomass in Climate Change A and B scenarios showed the impact on commercial fish species and on important migratory species with high conservation value (whales and shearwaters) simultaneously. Eroding beaches and consequently increased dredging, do impact commercial and conservation values. Such impacts are even larger when assuming a reduction in food availability and increased winter mortality due to warming ocean waters in Climate Change A and B. Mining due to beach erosion does not further compound the impacts due to warming ocean water

Figure 26 shows the spatial distributions of where sand lance biomass was predated in Massachusetts Bay and the New Jersey Coastal areas within the extent and resolutions chosen for the model. Simulations spanned 73 years at 1-day time steps. The predated Sand lance represents the value that these systems provide to commercial fisheries. The results reflect the outcomes of the reference scenario under the assumptions of no climate change, no dredging restrictions, and abundant sand resources. In comparison, predated sand lance seems more concentrated in New Jersey than in Massachusetts which can also be an artifact due to differences in resolution of polygons. In Massachusetts Bay, sand lance is very important for fisheries as it presents an important food source. We chose predated biomass to be an indicator.

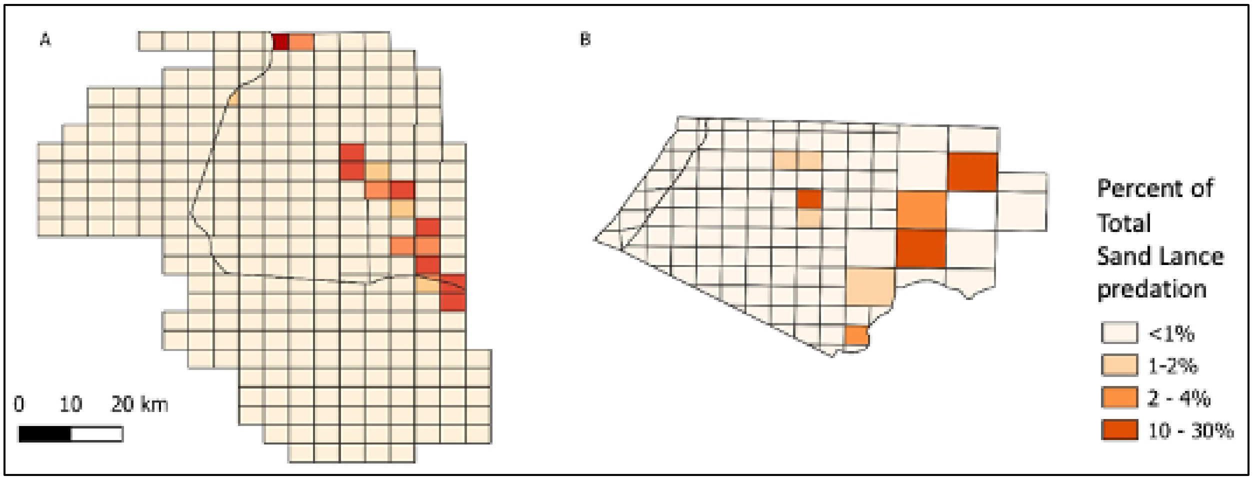


Figure 26. Predated sand lance biomass in SB-MIMES (left) and NJ-MIMES (right).
The results reflect the outcomes of the reference scenario under the assumptions of no climate change, no dredging restrictions, and abundant sand resources. Simulations spanned 73 years at 1-day time steps.

6.1.3 Species Richness

Species richness indicates the presence of sand lance and its predators in the area. In **Figure 27,** we compare species richness under different scenarios. We score species richness from 1–5 in each polygon using the availability of the following: 1) abundant sand lance population to attract 2) whales, 3) shearwaters, 4) mackerel and herring, and 5) groundfish. If all five species are present, the polygon gets a score of 5; the polygon receives a score of 1 if one species is present. Trends are down for all scenarios, with the steepest downward trend produced for Climate Change A and B scenarios. Species richness is the average number of species (sand lance + predators) per year for polygons, where sand lance populations emerge in the simulation. Higher numbers indicate more access of predators to sand lance either because populations exceed a feeding threshold or are booming when the predators are visiting the region. Dredging only affects sand lance populations when and where there is dredging (depths < 30 m and closest to shore), while climate change affects sand lance populations everywhere and potentially every year (which is noteworthy since sand lance buries mostly in water > 30 m). Peaks and valleys follow the dynamics assumed in the zooplankton input model. Clear peaks in MA are due to more zooplankton availability, faster growth of sand lance populations, and higher probabilities to exceed the biomass thresholds necessary to attract whales and sea birds.

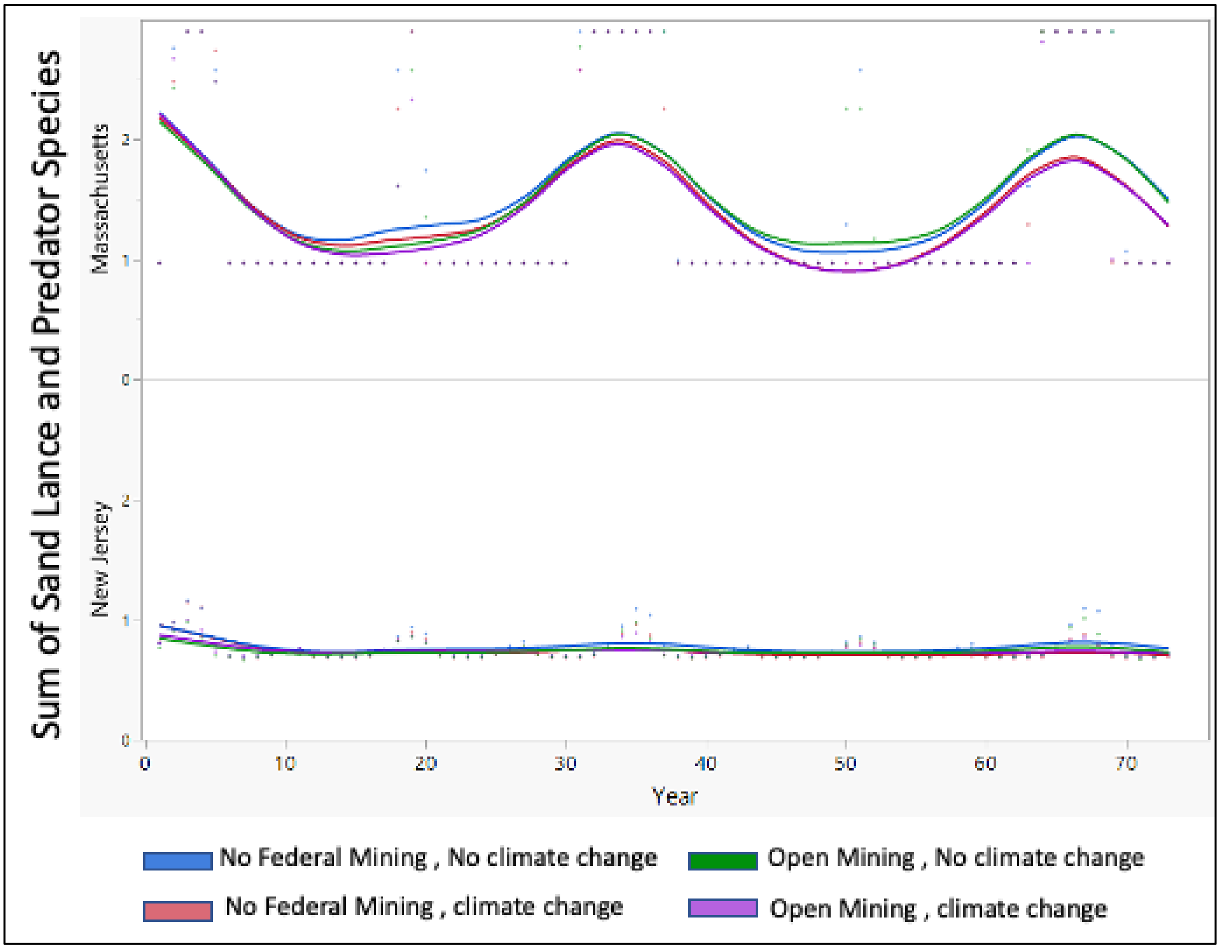


Figure 27. Species richness scenario visualization in SB-MIMES (top) and NJ-MIMES (bottom). Species Richness is the average number of species (sand lance + predators) per year for polygons, where sand lance populations emerge in the MIMES simulation. Higher numbers indicate more access of predators to the sand lance either because populations exceed a feeding threshold or are booming when the predators are visiting the region.

6.2 Socioeconomics of Sand Dredging Under Different Scenarios

MIMES models consider the annual amount of sand deposited and operation efficiency (the amount of sand mined, transported, and delivered per day) for each nourishment project. Beaches require different grain sizes, which impacts sand dredging efficiency as the sources for desired sand grain may be closer or further away from the beach that needs it. While sand dredging efficiency would decrease over time for a singular beach (best sands close to the beach get depleted first), regional sand dredging efficiency shifts from year to year as older nourishment projects are completed and the urgency for new beaches emerge where distances to the borrow areas are different.

Figure 28 displays trends in the efficiency of dredging and transport of sand from borrow areas to beaches. The units are in cubic yards of sand transported by a single dredge barge of standard hull volume. The results emerge from a 73-year period assuming 8 different scenarios for both of our study sites. The scenarios explore assumptions on climate change and management responses. Climate change scenario assumes that beaches will experience increased erosion, and that ocean water temperatures will increase. The management response assumes restricted access to Federal waters.

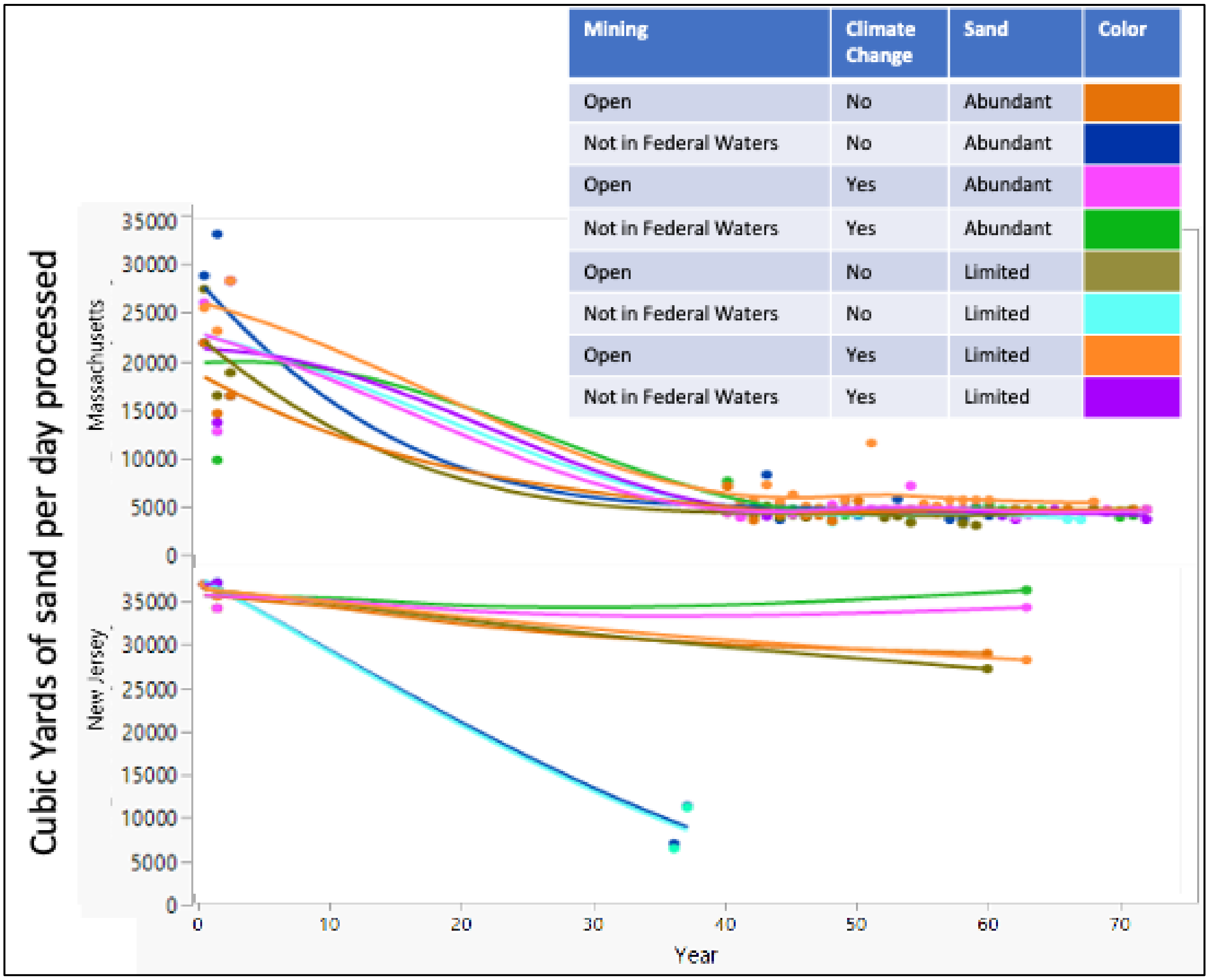


Figure 28. Trends in the efficiency of dredging and transport of sand in SB-MIMES (top) and NJ-MIMES (bottom).
The units are in cubic yards of sand transported by a single dredge barge of standard hull volume.

A limited resource availability assumes only half the sand available in contrast to the sand available under the abundant scenario. There is a stark difference between the behavior of beaches in New Jersey and Massachusetts mostly caused by the nature of the input data available for the first 40 years into the simulation. We used information on past trends of transgression and regression published by the New Jersey Beach Profile network (Hapke et al. 2013; NJBPN 2018) as our main information on past trends for the Massachusetts beaches. Trends after the first 40 years are set under the assumptions of the scenarios. The results for Massachusetts Bay indicate a decreased efficiency over time as dredge ships will have to travel larger distances after depletion of the borrow areas closer to the beaches. Results are not so clear for the New Jersey coast. Most likely the impact of the scenarios causes change in the order that beaches need nourishment where each beach is unique in its position to the appropriate borrow area.

When values are high, costs are high, and barges must travel a long distance to acquire the suitable sand for the beaches due to nourishing in that year. Prices are lower when beaches are closer to sand deposits with the appropriate sands. MIMES model yields annual outputs of costs by polygon—we can estimate the total cost for a beach with high home values and contrast with a beach with low home values. One of our takeaways is that wealth alters which beaches get sand renourishment done more quickly. MIMES can show that beaches with similar exposure have different urgency index values based on their local home value, resulting in different outcomes.

6.3 Sand Potential in Marine Areas

We described the beach exposure and urgency metric in Section 3.2. A beach is exposed when its sand volume is below the volume deemed to be safe. Exposure is measured in days and averaged per year for each beach shown in **Figure 29** (12 in NJ and 61 in MA). The initial exposure values reflect inaccurate estimates on the initial values for beach sand, an example of how the model could benefit from more observations. The different behaviors for New Jersey and Massachusetts and the switch at year 40 are due to variations in data availability. The main conclusion that can be gleaned from this output is that in New Jersey, only the open dredging scenarios will be sufficient to maintain safety for beaches. In all other scenarios (MA and NJ), nourishment projects will improve safety but never reduce exposure under 20 days per year. Beach communities need to be assured that there is enough sand on the beach to prevent flooding and wave erosion.

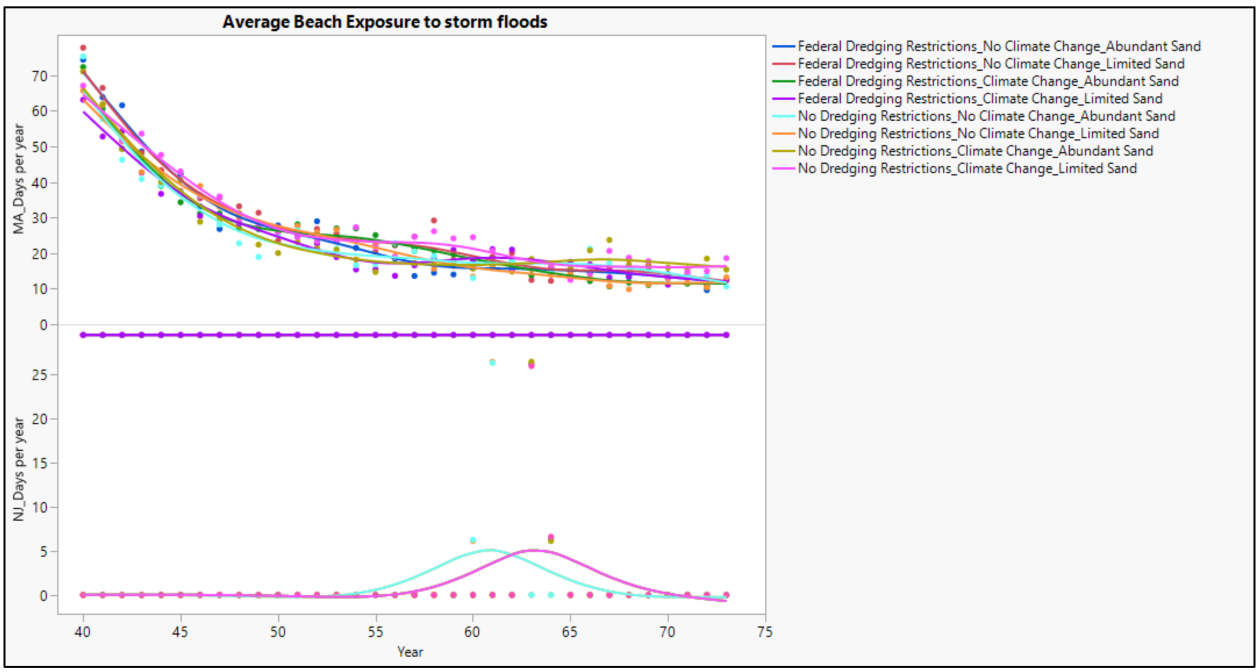


Figure 29. Average beach exposure measured in number of days per year under eight scenarios. Trends in the efficiency of dredging and transport of sand from borrow areas to beaches. The units are in cubic yards of sand transported by a single dredge barge of standard hull volume. The results emerge from a 73-year period assuming eight different scenarios for both regions.

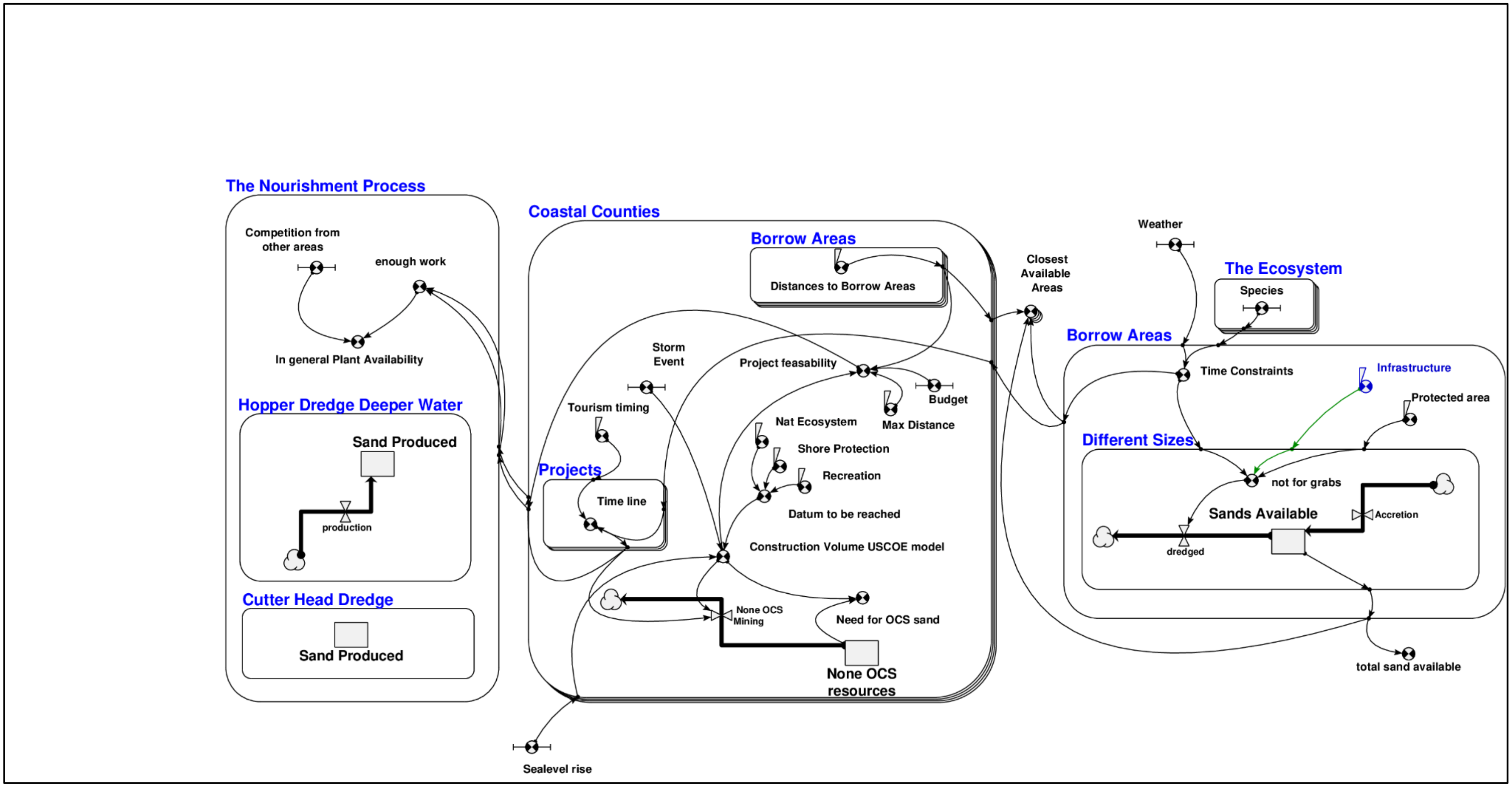
6.4 Conversations with Stakeholders

Much of the empirical data needed to address questions related to sand lance is being gathered by the institutions that partnered with BU including the SBNMS, WHOI, UConn, and others.

The interaction with BOEM (see BU-BOEM Status Report Feb 2020 Contract 140M0119C0013) and scientists at SBNMS (SBNMS, personal communication with authors, October 23, 2019) dictated the dynamics that we included in the model and provided ideas on what scenarios could be of most interest. These are discussed in Sections 3.5 and 4.

Sessions with scientists from BOEM and SBNMS scientists on October 23, 2019, are summarized through two stock flow diagrams (**Figure 30**). The differences between the diagrams highlights the differences in focus and expertise between the two groups. These diagrams are the building blocks representing expert knowledge later integrated into the MIMES decision tool.

No approach to understanding and making decisions about a system is perfect; models are inherently wrong as they can never fully capture the real world. The use of dynamic modeling for our immediate problem with sand and sand lance is not a replacement for alternatives that have been applied in this system. Rather, it is an enhancement that captures key considerations previously under-represented in decision-making, namely those delayed, surprising, and contingent impacts resulting from the complex and interconnected nature of CHANS. At the end of the day, all models are wrong, but some are especially useful (Lucas 2007); here, we aim to achieve more of the latter. Our modeling is affected by spatial resolution of the data, complexity of modeling, dynamic marine process, lot of missing models and uncertainty that introduce uncertainty. Such uncertainty can be addressed if any of the constraints change with better data, increased resolution, and advances in modeling.



The Nourishment Process
Competition from other areas
enough work
In general Plant Availability
Hopper Dredge Deeper Water
Sand Produced
production
Cutter Head Dredge
Sand Produced
Coastal Counties
Borrow Areas
Distances to Borrow Areas
Storm Event
Project feasability
Budget
Max Distance
Tourism timing
Nat Ecosystem
Shore Protection
Recreation
Projects
Time line
Datum to be reached
Construction Volume USCOE model
None OCS Mining
Need for OCS sand
None OCS resources
Sealevel rise
Closest Available Areas
Weather
The Ecosystem
Species
Borrow Areas
Time Constraints
Infrastructure
Protected area
Different Sizes
not for grabs
Sands Available
Accretion
dredged
total sand available

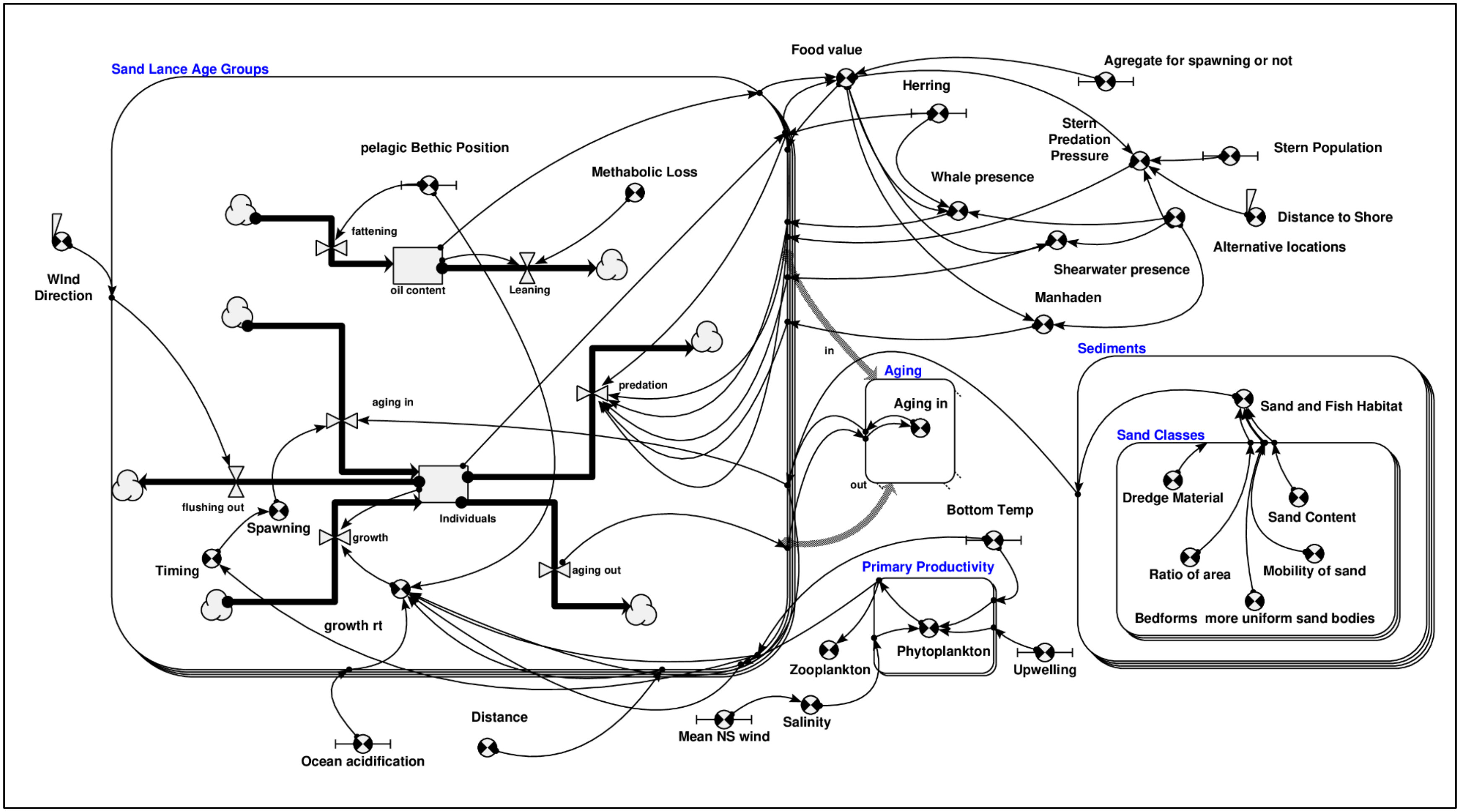


Figure 30. Scoping exercise with experts for sand lance dynamics and demand for sand in beach nourishment.
Top Panel: BOEM scoping model/demand for sand in beach nourishment: BOEM focus, the safety of coastal communities, the sourcing of appropriate beach sand, and the logistics of when and where to allow for sand dredging. Bottom panel: SBNMS scoping model/sand lance dynamics: sand lance habitat, food web interactions, and how such might be altered by changes in ocean conditions. A broader canvassing of stakeholders and broader engagement is needed.

7 Summary

To achieve our research goals, we used a system model designed to support decision-making related to sand dredging in New England and the Mid-Atlantic, informed by best available science. The project aims to provide scientific information on trade-offs from sand dredging strategies and options, highlighting places and times that will minimize consequences to the habitat and food supply of marine fishes and wildlife, specifically via the impact on sand lance and sand lance habitat, and the possible outcomes if mitigation is not implemented. It is important to note that sand lance are one piece of a complex puzzle regarding trade-offs from sand dredging; managing dredging is therefore based on a number of impacts to different resources. For example, strategies to minimize effects to sand lance may increase effects to endangered or threatened species (i.e., piping plovers). Integrating available data into the MIMES modeling framework will permit anticipation of otherwise unexpected ecological effects and will reveal how impacts emerge in space and over time. These outcomes make it possible to more fully grasp and potentially minimize the costs associated with sand dredging. Developing models in both New Jersey and Massachusetts leverages an area of existing interest for sand dredging alongside one of extensive biological and ecological knowledge and data, and brackets a larger area that could be assessed in future work.

7.1 Conclusions

Exploration of varied dredging and climate change scenarios using MIMES yielded several insights that are potentially important for decision-making regarding where and when to dredge sand needed to maintain our protective and economically critical beaches and coastal ramparts. A few of the most important conclusions are summarized here.

There are several key points that emerge from the MIMES model and MIDAS visualizations as informed by the fieldwork led by the SBNMS. First, dredging offshore in Federal waters is probably less damaging ecologically than dredging in state waters, near the coast. This is due to the high concentration of both wildlife and fisheries along the coast, particularly during seasonal migrations (Staudinger et al. 2020). However, dredging closer to shore is much less costly in terms of logistics and transport. The result is that the area of Federal waters just outside state jurisdiction should be looked at closely as a desirable region for sand dredging, provided appropriate deposits are present there and contingent upon the sand grain size. These waters under Federal jurisdiction are suitable for dredging but safely distanced from the intense ecological processes along the coast, including the life histories of species in peril (e.g., piping plover, roseate tern, and least tern).

It is critical to remember that as climate change progresses; the demand for sand will rise, while the practicality of keeping up with erosion will fall (Cooke et al. 2012; Parkinson and Ogurcak 2018; Schlacher et al. 2007). At some point, sand dredging and beach renourishment become ill advised as a climate change adaptation strategy. Given the inevitability of this point of diminishing returns, considering alternative solutions (e.g., re-imagining coastal land use and real estate) is highly recommended.

Second, scenario modeling is a useful tool for EBM. Even when uncertainty is high, having a clear idea of potential outcomes and their relationships to intervention options can be critical for decision-making. The power of this approach lies in the ability to use prior studies and empirical knowledge from one area to reveal functional connections that are also operating in other places. The modeling is transportable, though improved with the addition of local knowledge. As knowledge across a variety of sites advances, a broader understanding emerges and more informed decisions can be made in new areas. An integrated, cross-disciplinary approach is essential to decision-making but is not yet all-encompassing. Another crucial aspect that we did not consider here, as it was outside the scope of this study, is social justice; options for including this aspect of data gathering should be explored moving forward.

Detailed knowledge of sand lance life history and biology is also critical to the success of this model. This is just one example of a broader, and perhaps worsening, weakness in our knowledge of natural history. While a computational model is an invaluable tool for synthesizing large amounts of data and exploring potential scenarios, it is only as good as the data that are imported and the wisdom with which it can be interpreted. An investment in coastal and continental shelf marine science will therefore improve these types of models. While theory and modeling can extend the power and utility of limited local observational data, if they get too far ahead of validation and ground truthing, the modeling results will increasingly stray from reality. We were able to avoid this in part because our modeling efforts were closely tied to concurrent empirical studies.

The enormous importance of forage fishes, such as sand lance, to the viability of both commercial and recreational fisheries is well established. In this study model, we captured this relationship through an estimate of cumulative predation on sand lance. This is governed by several key parameters: growth in biomass of sand lance, density of sand lance at which predators regard it as a preferred prey and begin targeting it specifically, and presence of commercial species known to be sand lance predators in a study area at any given time. The growth in biomass of sand lance is a function of larval supply, food supply, and temperature. Larval supply is influenced by the movement of cold-water masses south from larval source areas to the north, which we know from our fieldwork and from transport modeling conducted by our WHOI partners for this study.

Food supply (and quality) are also related to cold-water masses (and therefore oceanography), since the richest prey species, the copepod *Calanus finmarchicus*, is a cold-water species. We have not yet coupled our model to a physical oceanographic model (a very complex task that is needed and would be a useful national resource), so in our model these are parameter settings that can be explored through sensitivity analyses (repeated runs with different parameter values). Temperature has multiple effects on the delivery of prey and sand lance larvae, on feeding and growth rates of the sand lance and their prey populations, on the arrival and activity of sand lance predators, and most critically, on winter survival of the young-of-year sand lance (Year Class 0). Northern sand lance is a nutrient-rich and important prey, so it would be reasonable to expect relationships between predator distribution, abundance, and growth in sand lance population metrics.

However, this is not the only factor bearing on the influence of sand lance population fluctuations on commercially important fish species (many of which prey on sand lance). Sand lance are not the only forage species in the system. For example, juvenile Atlantic herring, menhaden, alewife/blueback herring (the river herrings), juvenile ground fishes (especially hakes), butterfish, and squids can also be important. Our model does not take into account the influence of alternative prey for commercially fished species as that would require work beyond the mandate of this contract and would also benefit from better data on forage species and predator-prey relationships than are currently available. In general, the forage species diversity will tend to offset the impacts on sand lance populations, but we cannot yet know exactly how much or when, and where.

Sand lance are also critical to ecosystem function, wildlife, and biodiversity in a broad sense. As previously indicated, our work revealed that the success of northern sand lance, a high-latitude species along the US Atlantic Coast, is largely dependent upon oceanographic dynamics to the north to deliver annual year classes farther south, ensure overwintering survival of adults, and provision both young and adults with the richest and most important zooplankton prey. In other words, southern portions of the northern sand lance range are likely to be highly vulnerable to climate change since they are at the edge of their range. We do not know to what extent the American sand lance or other forage species can substitute as seawater temperatures continue to rise.

In addition to this north-south connectivity that merits close observation, there is an onshore-offshore connectivity that involves the two sand lance species, the northern (*Ammodytes dubius*) and the American (*Ammodytes americanus*). Northern sand lance populations are concentrated on the OCS. This species grows larger than the American sand lance and is a major OCS forage species. The American sand lance is most abundant close to shore or on beaches, though it overlaps with the northern sand lance at depths of 10 m to 20 m (personal communication with authors, 2012). In this study we did not fully explore the complexities raised with two sand lance species in one study area. For example, a state may desire to dredge sand within its jurisdictional waters but not want to accept the trade-offs with nearshore fishing. However, they will not want to go any farther offshore than necessary due to costs. This places likely sand dredging in many cases somewhere near the state line or just over the line in the nearest sand resources available in Federal waters, a boundary that is ecologically meaningless. Such activities could impact *both* species of sand lance, which is important to consider as less is known about the American sand lance that lives on beaches and nearshore sand shoals. Dealing with these complexities demands an improved understanding of ecological substitutability within the forage guild and close cooperation between Federal and state governments in ocean planning. Coastal decision-making requires an integrated, cross-disciplinary approach, and scenario modeling is a useful tool for achieving it.

Finally, the most important management implications from this study, with regard to sand dredging for beach renourishment, are as follows:

- The habitat preference for sand lance largely coincides with target areas for sand dredging.
- The use of a computational trade-off model can assist in minimizing the impacts of dredging on other ecosystem services and values.
- Reduction of biological impacts must also be reconciled with economic constraints.
- With all this in mind, sand dredging is best directed within a zone that is far enough from the coastline to minimize impacts on the food supply of estuarine fishes and threatened bird species, but close enough to be economically favorable. With respect to sand deposits under BOEM's jurisdiction, this relates to areas in Federal waters near, and adjacent to, the state water boundary.
- In addition, there is likely a best time of year to dredge so as to minimize impacts on benthic communities. In sandy habitat, the concern is for "old" or "mature" bottoms (i.e., sand that has been stabilized by mature benthic communities and is full of tube-builders and epifauna), which should be avoided. The benthos follow an annual cycle, building up over the early winter into spring, and then ebbing as predation takes its toll. Thus, the favorable window for minimal-impact dredging is likely in the fall; however, this may vary locally.

7.2 Future Applications

This study is specific to understanding the productivity and ecology of sand shoals, the potential for sand dredging to disrupt fisheries, and the means to minimize such disruption. However, the MIMES approach provides additional and readily available avenues to further support BOEM's work in other areas. In particular, wind farm development in our study area involves similar trade-offs between development and protected species and wildlife considerations, and the existing MIMES model was originally built to investigate trade-offs around wind farm development. Here, our model can further assess interactions with currently proposed wind farms and potential trade-offs, especially with respect to wildlife (i.e., protected species). If valuable, this could leverage previous work supported by BOEM by integrating earlier studies on protected species (i.e., marine mammals and sea turtles), seabirds, and fisheries into the model design and allow additional trade-offs to be assessed along with consequences of alternative management decisions. As with the results related to sand dredging, MIMES could readily provide decision support regarding BOEM's work in renewable energy. The ecosystem valuation based MIMES model is applicable in several BOEM projects, including mineral extraction, biodiversity management, and offshore wind energy development. The model and data resources are available to make this additional element readily possible.

8 References

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Appendix A: Supporting Information

MIMES applications follow the architecture in model development described in a prior study (Fitz et al. 1996) that proposed using a unit model as a node for implementation into a spatial network to achieve spatial dynamic simulations. The BOEM MIMES application aims to explore the trade-offs among beaches that require sand for nourishment and marine locations that can be mined for that sand. The dynamic spatial nature of the model allows for elucidating trade-offs among locations and across time among various social groups. We developed unit models for upland and marine dynamics coupled to capture upland marine interaction dynamics in the model. The unit model for upland dynamics simulates beach erosion processes and management responses to secure flooding protection for coastal communities. The marine unit model simulates sand lance population dynamics. Sand lance is a feed fish important as a link between oceanic photosynthetic production and the existence of commercial fish species, marine mammals, and seabirds, together representing the fishing industry's interests and conservation. The upland marine interaction model simulates the dredging operation to facilitate the coupling interactions between the beach and marine models and represents the trade-offs' financial costs and the economic price.

The coupled unit models are applied to simulate two different coastal regions—one for Long Beach in Ocean County, New Jersey (NJ-MIMES), and one for SBNMS and Massachusetts Bay off Massachusetts (SB-MIMES).

The model concepts, on what are important dynamics to consider, were scoped out in meetings with the scientists at SBNMS and the BOEM team and are not meant to be the last word on these matters. The transformation from the scoping to a research model to explore the concepts under scenarios requires specification and parameterizations of equations to the best available information.

Such information comes from knowledge (understanding of how the system works), data (observations in space and time), and parametrization (rates and dimensions), all prone to uncertainty. It is essential to build confidence in the models' outcomes to consider these uncertainties. Improving the understanding of how the system works enhances the accuracy; more dedicated observations are likely to provide better data and improve the precision. Future development of the models will require consideration on how the investment into gathering more precise and better data will improve accuracy at the level necessary in decision-making.

A.1 The Beach Unit Model

The beach unit model is designed to include the dynamics that enter the decision-making process when the following questions are asked:

- Will this beach ever be considered for a nourishment project?
- What is the preferred volume of sand on the beach?
- How much do we like, or can we afford to overfill the beach beyond its preferred volume?
- What is the expected period of organizing a nourishment project (raising the money, securing the permits, and organizing the work)?

To address these questions, the beach unit model follows the dynamics of sand:

$$\frac{dB^i}{dt} = B_t^i + N_{Fed,t}^i + N_{St}^i - E_t^i$$

Equation 1

In this equation B^i is the sand on beach at location I in cubic meters of sand per linear meter of beach (m^3/m). ($N_{Fed,t}^i$) is the nourishment sand sourced from Federal waters, ($N_{S,Depth}^i$) is the nourishment sand sourced elsewhere and E_t^i is the erosion. (N_{St}^i) requires external data import and is outside the scope of this study (set to 0). E_t^i is the erosion term either estimated from the USGS study (Hapke et al. 2010) or imported as observed data as in the New Jersey application (NJBPN 2018).

$N_{Fed,t}^i$, is the upland-marine interaction and represents the sand per day in a nourishment project that a hopper barge is able to mine and transport from a borrow area and deposit on the beach location (i) with highest urgency (U).

If and where the project will take place depends on the ranking of U values among the beach locations. Beach i is most urgent if a project is ongoing (sand mined at t-1 >0) and is not yet completed (Sand_Demand>0). Sand Demand ($SD_t^{1,i}$) is the Desired Beach Volume ($DBV^{1,i}$) modified by a nourishment design option for Over Filling ($OF^{1,i}$) compared to the sand already on the Beach ($B_t^{1,i}$)

$$SD_t^{1,i} = max(0, (OF^{1,i}DBV^{1,i}) - B_t^{1,i}) \text{ Equation 2}$$

If no nourishment projects are underway, the model again estimates a metric of urgency for such projects at the remaining set of beach locations. To be deemed urgent, a beach needs to reaches a Sand Deficit Volume ($SDV_t = DBV_t - B_t$) larger than $50m^3/m$ and hold a value of capital investment larger than 0.5$M. Beaches meeting these requirements are assigned an urgency value (U) in ranking the multiplications of house values (in $M) by SDV_t. 1

A.2 The Marine Unit Model

The marine unit model simulates dynamics of a sand lance population within habitat conditions, and is designed to address the following questions:

- What is the effect of dredging on sand lance populations?
- What is the effect of habitat destruction on sand lance populations?
- How do sand lance populations contribute to commercial and conservation interests?

The sand lance populations unit model is formulated within the following equation:

$$\frac{dFBM^{1,i}}{dt} = g_t^{1,i}\left(1 - \frac{C_t}{FBM_t^{1,i}}\right)FBM_t^{1,i} - (m_t + p_t^{1,i})FBM_t^{1,i} + \left(Ain_t^{1,i} - Aout_t^{1,i}\right) + \left(Din_t^{1,i} - Dout_t^{1,i}\right)$$

Equation 3

Where $FBM^{1,i}$ is the sand lance fish biomass of age classes 1 to i, $g_t^{1,i}$ is the growing rate, c_t is the carrying capacity, $Ain_t^{1,i} and\ Aout_t^{1,i}$ are fish aging either into or out from the age classes 1 to i, and $D_t^{1,i} and\ D_t^{1,i}$ is biomass either dispersing in or away from the location.

The $FBM^{1,i}$ at time = 0 represents the initial biomass in each of the age classes. In testing the unit model, we assumed only biomass at a value of 1 to be available for age class 2 (larvae) to simulate the establishment of a new population shown in **Figure A1**.

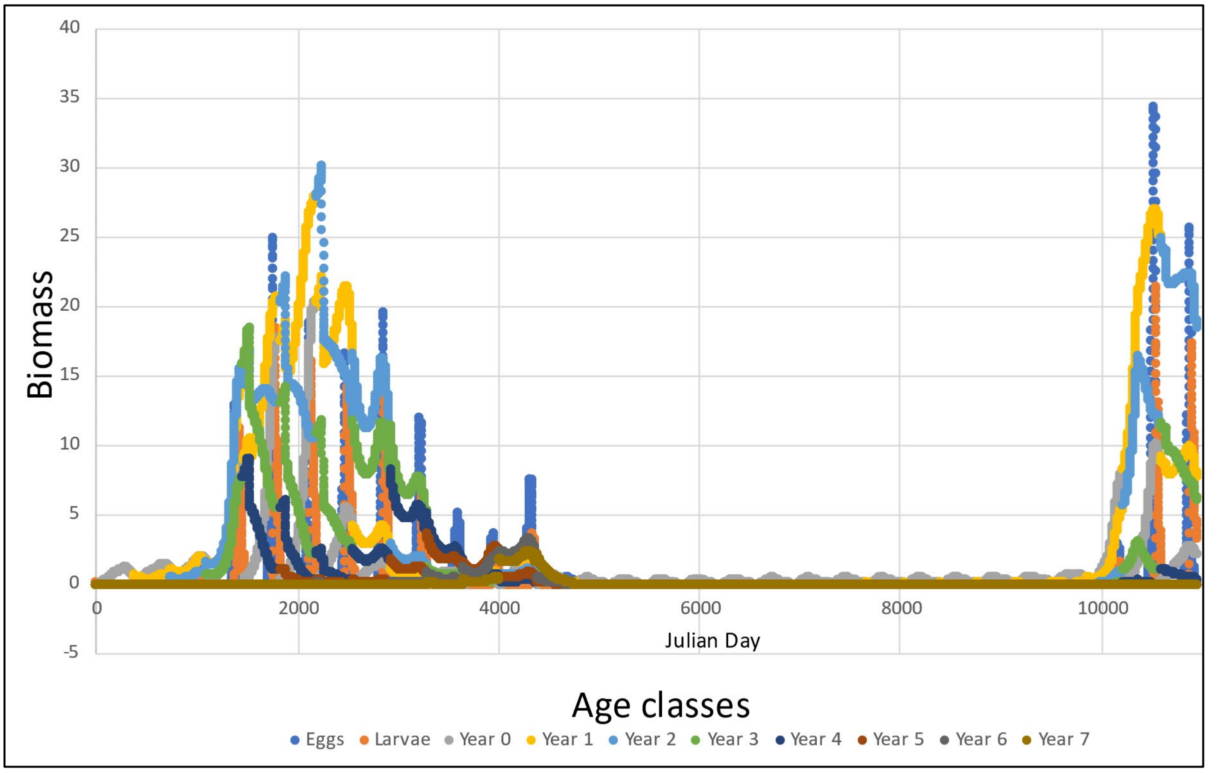

Figure A1. Example output of the sand lance dynamics within the marine unit model along a period of 30 years.
Biomass is in tons of carbon, not calibrated against observations. The model mimics observations of sand lance populations alternating between abundant and lean periods.

A.2.1 Sand Lance Growth Rates

The growing rates for each age class ($g^{1,i)}$, except for eggs (g^1), follows the development in total population oil content (OC_t):

$$g_t^{1,i} = \frac{OC_t}{10} mg^{1,i}$$

Equation 4

Although sand lance will survive on a variety of zooplankton species, in years when *Calanus spp*. are abundant, the fish is able to increase its biomass oil content to allow faster growth and decreased mortalities. *Calanus* thrives in cold water and is impacted by warming waters so that *Calanus* and subsequently sand lance populations are most likely impacted by increases in global temperatures.

$$\frac{dOC^{1,i}}{dt} = OC_t^{1,i} + (Fat_t - Lean_t)$$

Equation 5

Fat_t is the rate at which oil is gained, $Lean_t$ are the processes at which oil is lost.

Fat_t requires two conditions: sand lance needs to be up in the water column foraging and not buried in the sand (field observations; **Figure A2**), and *Calanus spp*. biomass needs to be available. The rate of fattening is proportional to the available *Calanus* biomass, bounded by the maximum oil increase capability of the sand lance population present ("$Calanus\_need$").

$$Fat_t = \frac{(Calanus, Calanus\_need)}{co}$$

Equation 6

The variable "Calanus" requires external input and offers the opportunity to inform the model from observations (Eco Mon or other data sets) or be informed by the outputs of zooplankton simulations such as "PISCES" (Aumont et al. 2015). As the marine areas we are modeling are warming due to climate change (ref), we expect *Calanus .spp*, to be compromised over time. In the scenarios and indicator chapter we present a scenario generating model developed to simulate potential dynamics and magnitudes of *Calanus* declines in exploration of the sand lance population dynamics.

$$Calanus\ need_t = GC \sum \quad FBM_t^{1,i}$$

Equation 7

$Lean_t$ represents the loss of oil either through the fish metabolism or spawning of the eggs.

$$Lean_t = max(0, OC_t^{1,i})((ol * Spawning\_time) + ol)$$

Equation 8

$Spawning\_time$ follows observations and is imported into the model from the vulnerability matrix (**Figure A2**).

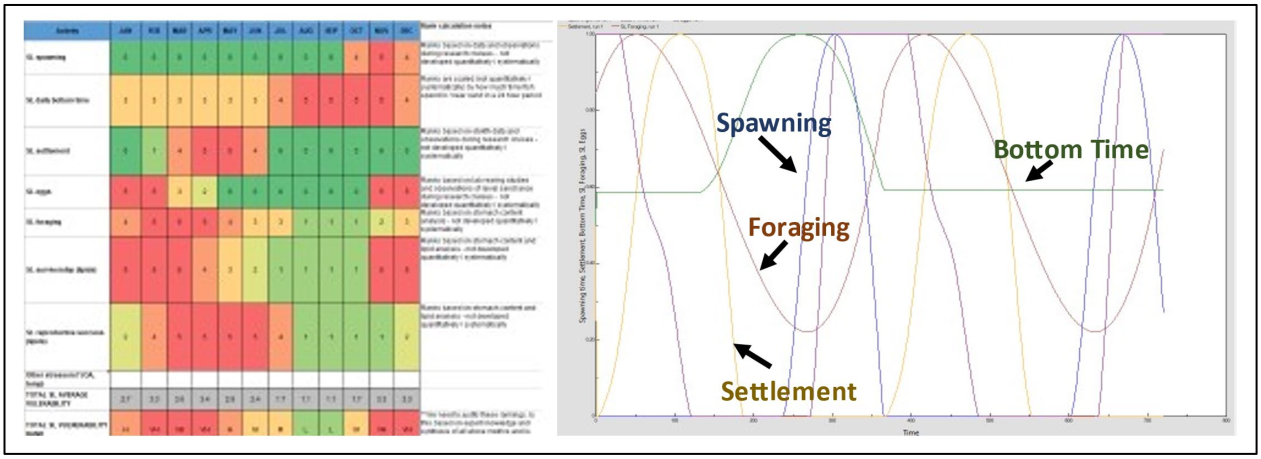

Figure A2. Vulnerability matrix.
SBNMS Expert opinion on the vulnerability of sand lance to dredging used as input data to inform the sand lance cohort model.

A.2.2 Sand Lance Mortality

$(m_t + p_t^{1,i})FBM_t^{1,i}$ represents sand lance mortality where m_t is a population mortality rate and $p_t^{1,i}$ is an age group specific predation rate. While both rates are influenced by the population oil content, additional causes of mortality are due to dredging or when bottom surface temperatures in winter are higher than 7C° (Staudinger et al. 2020).

The Population Mortality rate

$$m_t = \frac{1 - \frac{OC_t}{15}}{45} + mining\ mortality + winter\ temperature\ effect$$

Equation 9

The model assumes the mining mortality as to be a percentage of the total sand lance population when harvesting occurs in an area. Due to the lack of information, the model does not consider this mortality to be proportional to the harvesting effort.

The mortality due to winter temperatures of the ocean bottom was documented by Staudinger (Staudinger et al. 2020) and is of importance when considering the effects of climate change on seawater temperatures. The model derives sea bottom temperatures from sea surface temperatures and depth. As depths increase, temperatures decrease to a minimum of 4C° when water is at its highest density. When formulated this way, winter mortalities are more prone to occur in shallow water and set the upper depth boundaries for sand lance population establishment.

Predation pressures

The model considers the presence and activity of four distinct predators ($Pred_t^{1-J}$; whales, shearwaters, herring and mackerels, and ground fish) to derive predator pressures on each of the sand lance age group predation pressures. Predator predate when they are present (($Ypred_t^{1-J} * Spred_t^{1-J}$)), interested in feeding ($\frac{OC_t}{OC_{max}}$), can reach the prey ($Prey\ access_t^{1-j}$), encounter appropriate prey biomass ($MinFB^{1-j}$) and have that age group as their prey target ($BM\ Target\ _t^{1-J,1-i}$; $table$)

$$p_t^{1,i} = \frac{OC_t}{15} * \sum_{1\ to\ j} Pred_t^{1-J} * BM\ Target\ _t^{1-J,1-i}$$

Equation 10

$$Pred_t^{1-J} = (Ypred_t^{1-J} * Spred_t^{1-J}) * \frac{OC_t}{OC_{max}} * Prey\ access_t^{1-j} * \max(0, (\sum FBM_t^{1,i} - MinFB^{1-j}))$$

Equation 11

$$Prey\ access^{1-j} = max(Benthic\_Reach^{1-j}, Bottom\_Position_t^{1-i})$$

Equation 12

Whales are interested in feeding when the sand lance population reaches above a minimum threshold, shearwaters are interested in feeding when sand lance are in the water column and not buried in the sand. Both whales and shearwaters visit on a seasonal basis. Herring, mackerels, and groundfish are always present, but experience year-to-year population fluctuations. They are assumed to have preference for the younger sand lance age classes. Adding predator population dynamics prepares the model for an opportunity to couple these sand lance dynamics with a more complex food web model and interaction with ocean management (Altman et al. 2014).

A.2.3 The Aging of Sand Lance Cohorts

$$if\ i = 1\ then\ Ain_t^i = E\ else\ Ain_t^i = Aout_t^{i-1}$$

Equation 13

Aging in ($Ain_t^{1,i}$) is the flow entering age class i+1 from age class i.

Aging out $Aout_t^{1,i}$ is the flow of sand lance biomass leaving age class i to enter age class i+1. E_t is the egg biomass entering age class 1 at a spawning rate (Sp_t) (**Figure A2**). The extent of eggs entering age class 1 (Ain_t^1) is proportional to the population biomass and modified by the population age as fish of different ages can have differences in egg production per biomass ($e^{1,i}$). When eggs are hatching (Ain_t^2) at the hatching rate H_t, biomass flows from eggs into a larval stage H_t is proportional to E after being delayed by an incubation period (ip). Sea Bottom Temperature (SBT) influences the rate of incubation so that warmer SBT cause a shorter ip than colder SBT (reference).

$$SBT_t = (max(0, SST_t - DTemp)$$

Equation 14

Settling onto the sand (Ain_t^3), flows larval biomass into the 0_year age class at settling rate (S_t ; vulnerability matrix). It takes about 3 months for eggs to reach the 0_year age class. Once biomass enters

0_year age class it continues to flow along the following year classes every last day of the year (December 31) to ultimately reach the last age group of 7 year and older ($Ain_t^{4,10}$).

$$Ain_t^1 = Sp_t * \sum (FBM_t^{1,i} * e^{1,i})$$

$$Ain_t^2 = H_t * FBM_t^1$$

$$Ain_t^3 = S_t * FBM_t^2$$

$$Ain_t^{4,i} = if(Jday = 365, FBM_t^{3,i-1}, 0)$$

Hatching rate (H_t):

$$H_t = if\ (ip < 1), 0\ , Sp_{t-\lceil ip \rceil})$$

Equation 15

$$ip_t = \sum \quad if\ (incubation_t > 1,1,0) - \text{if}(\text{Jday}=100, ip_t, 0)$$

ip is reset to 0 on March 4th (Julian Day (Jday) = 100) to mark the end of the spawning and hatching season.

$$\frac{dIncubation}{dt} = incubation_t + \lceil Sp_t \rceil (0.0072917 + 0.0026042 * SBT_t)$$

$$SBT_t = (max(0, SST_t - DTemp)$$

Equation 16

A.2.4 Dispersion of the Sand Lance Larvae

$Din_t^{1,i}$ *and* $Dout_t^{1,i}$ represent fish biomass either drifting in from other marine locations or leaving the location. They are available in the unit model to test the sensitivity of an in and outflux of larvae to a population but gain in importance in the spatial model for connecting populations to each other through spatial dispersal of larvae.

A.3 Sources of Uncertainty Associated with the Marine Unit model

Not included in the model are the food web feedbacks between the predators and prey populations so that sand lance populations seem to be influenced more by bottom-up processes (the availability of *Calanus spp* and the impact from winter mortality) than by the top-down processes of predation. There is the potential that shifts in the marine ecology causes other feed fish to invade and provide sustenance to predators in lean sand lance years. By including a full food web model, top-down processes might gain more importance within the model results. Also not included in the model are the effects of commercial fishing on sand lance populations.

Not established are the nature of ecosystem shifts with climate change:

1. Do predators shift diet to another forage fish?
2. What are the effects of climate change on *Calanus spp*. populations?
3. Where and to what effect do bottom temperatures shift during winter when adult sand lance is buried and lean from spawning?

Many of the parameters setting the rates for life history have not been measured. Impact of these sources of uncertainty on model results relevant to the biomass of sand lance, distribution and its availability to predators.

In particular:

- Growth, mortality, and survival of sand lance cohorts as modified by the absence or presence of *Calanus spp.* (understanding the feeding and lipid relationships).
- The effects of dredging activities (sediment plume, direct impact with the dredging equipment, and the influence of warming winter temperatures on mortality).
- The timing and drivers of spawning, hatching of eggs, settlement of te larvae, and maturing of the 0-year class.

A.4 Model Parameterization

Parameters setting rates for sand lance are shown **Table A1 and parameter setting conditions for predators to have access to the sand lance are in Table A2**.

Table A1. Parameters setting rates for sand lance

Parameter	Units	Value(s)	Interpretation
$mg^{1,i}$	$gg^{-1}d^{-1}$	0.01	Maximum growth rate
GC	gg^{-1}	6	Max grams of *Calanus* intake per gram of sand lance biomass to reach maximum oil uptake
ol	$g^{-1}d^{-1}$	0.01	Oil loss from spawning
Mth_rt	$gg^{-1}d^{-1}$	0.0002	Oil Metabolic rt
co	gg^{-1}	1,000	*Calanus* availability to oil production conversion factor

Table A2. Parameters setting conditions for predators to have access to the sand as a food source

Pred_ID	Predator	Min SL_BM	Benthic Reach
1	Whales	100	1
2	Shearwaters	100	0
3	Mackerel and herring	10	0.5
4	Ground fish	10	1

Notes: Min_SL_BM is the biomass threshold that a sand lance population needs to reach to be noticed by the predator. Benthic Reach signifies the ability of the predator to reach sand lance for prey. Whales with a value of 1 will always be able to feed from the bottom, while shearwaters will never be able to reach the sand lance when buried in the sand.

Sand lance–predator interaction settings are shown in **Table A3**. Value is an estimate of the ratio of the sand lance population that predators can consume in one day.

Table A3. Sand lance–predator interaction settings

Sand Lance Age Group	Ground Fish	Herring and Mackerel	Shearwaters	Whales
eggs	0.5	0	0	0
larvae	0	0.5	0	0
Year 0	0.3	0.2	0	0.3
Year 1	0.3	0.1	0	0.7
Year 2	0.3	0	0.1	0.7
Year 3	0.3	0	0.2	0.7
Year 4	0.3	0	0.2	0.7
Year 5	0.3	0	0.2	0.7
Year 6	0.3	0	0.2	0.7
Year 7	0.3	0	0.2	0.7

MIMES models (**Table A4**) mortality, where setting NWM indicates no winter mortality, WM indicates winter mortality. Bls assumes limitations to the sand resources. Above T_max sand lance mortality is set to increase by temperature. **Table A5** shows the parameter settings for different age cohort attributes.

Table A4. MIMES model mortality

Model Focus	Parameter	Units	NWM	NWM_ls	WM	WM_ls
Sand Resource	Sand Depth	m	2	1	2	1
Sand Resource	TSS	g*m^3	0.02	0.02	0.02	0.02
Sand Lance	Oil cal	Percent	60	60	65	65
Sand Lance	Monitoring	On-off	0	0	0	0
Sand Lance	Calanus Needed	ratio of BM	6	6	6	6
Sand Lance	T_max	°C	15	15	7	7
Sand Lance	Temp death rt	ratio	0	0.5	0.5	0.5
Nourishment	Load Volume	cu m	4,000	4,000	4,000	4,000
Nourishment	Max Water Depth	m	50	50	50	50
Nourishment	Over Filling	none	1.5	1.5	1.5	1.5
Nourishment	Project Development Time	days	350	350	350	350

Table A5: Examples of scenario parameters setting

Cohort	EggBM_ratio	Habitat	Mort rt	Turbidity Effect on Mortality	Mining Mortality	Max Growth rt
Egg	0	1	0	0.001	0.1	0
Larvae	0	2	0.005	0.001	0.1	0.03
Year 0	0	20	0.01	0.001	0.1	0.03
Year 1	0.0125	30	0.01	0.001	0.1	0.03
Year 2	0.025	2	0.05	0.001	0.1	0.03
Year 3	0.03	2	0.05	0.001	0.1	0.03
Year 4	0.035	1	0.05	0.001	0.1	0.03
Year 5	0.04	1	0.05	0.001	0.1	0.03
Year 6	0.045	1	0.05	0.001	0.1	0.03
Year 7	0.05	1	0.05	0.001	0.1	0.03

Time data inputs are shown in **Figure A3.** "Day-to-day" reflects the seasonality of migrants such as whales and shearwaters. Year-to-year variations allow input into the model when predator populations vary over the years.

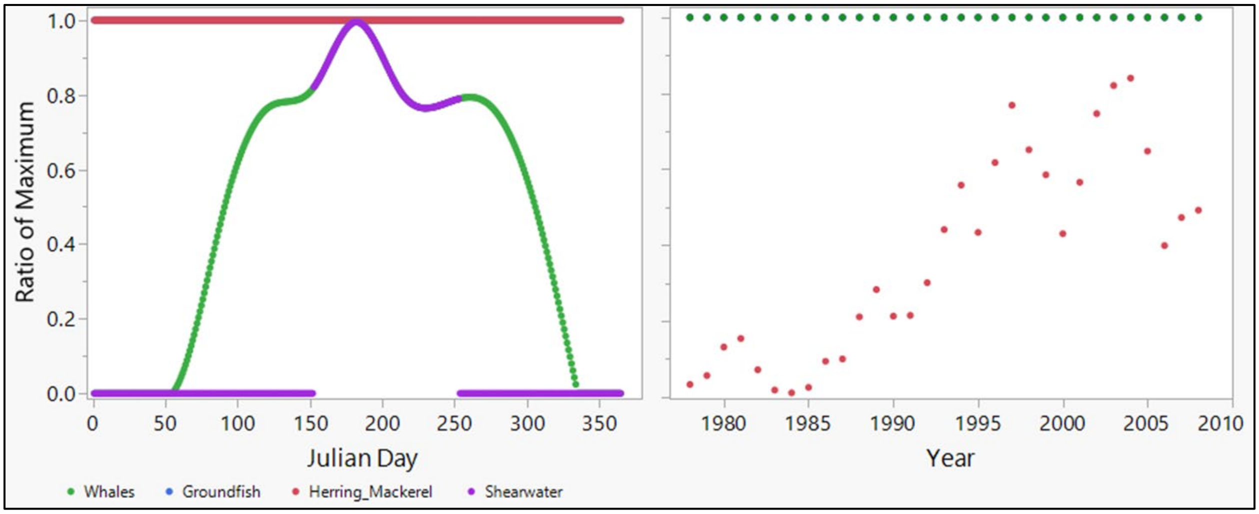

Figure A3. Model inputs on day-to-day and year-to-year variations in the presence of predators. Only herring and mackerel populations are set to have year-to-year variations. Whales and shearwaters are set to have seasonal variations.

A.5 Climate Change Scenarios

Climate change impacts are explored using the model outputs for changes expected in the availability of food for sand lance (i.e., *Calanus spp*), warming of sea water, and its effect on sand lance winter mortalities (both included in the Climate Change A assumptions), and increased erosion rates at the beaches (assumptions within the Climate Change B scenario). Potential effects of climate change not included in the exploration through scenarios are assumptions that predators shift diet to another forage fish. Note that MIMES climate change is not calculated through IPCC global change models. MIMES models climate change assuming changes in ocean bottom temperatures and its impact on zooplankton populations. Hence climate change in this context is only using expected changes in ocean temperatures based on depth criteria.

The *Calanus spp.* model:

$$Cal_{t,l} = ECal_l \sum_{n=1}^{n=3} \left(\left(A \cos \cos \left((2\pi/\lambda_{cm,1-3}) \varphi_{cm,1-3} \right) \right) + \left(A \sin \sin \left((2 * \pi/\lambda_{sm,1-3}) \varphi_{sm,1-3} \right) \right) \right)$$

$$\varphi_{m,1-3} = 365 - \omega_{1-3}$$

Equation 17

$$A = \underline{A} \sum_{n=1}^{n=2} \left(\left(A \cos \cos \left((2\pi/\lambda_{cy,1-2})\varphi_{cy,1-2} \right) \right) + \left(A \sin \sin \left((2 * \pi/\lambda_{sy,1-3})\varphi_{sy,1-3} \right) \right) \right)$$

$$\varphi_{y,1-2} = (p_{1-2} * 365) - \omega_{y,1-2}$$

Equation 18

Where $Cal_{t,l}$ is the *Calanus* concentration at location l ($mg*l^{-1}$), and $ECal_l$ is the ratio of measured *Calanus* concentrations at a location over the maximum concentration within the region. The model provides for a set of three wave forms, combinations of sine and cosine waves, to capture seasonal dynamics, and a set of two wave forms to capture year-to-year dynamics in the amplitudes (A) of the seasonal waves.

The model allows the exploration of hypotheses on changing seasonal dynamics (variations in λ_m), year-to-year dynamics (variations in $\underline{A}$), and changes in year-to-year dynamics (variations in λ_y). These dynamics are shown in **Figure A4**.

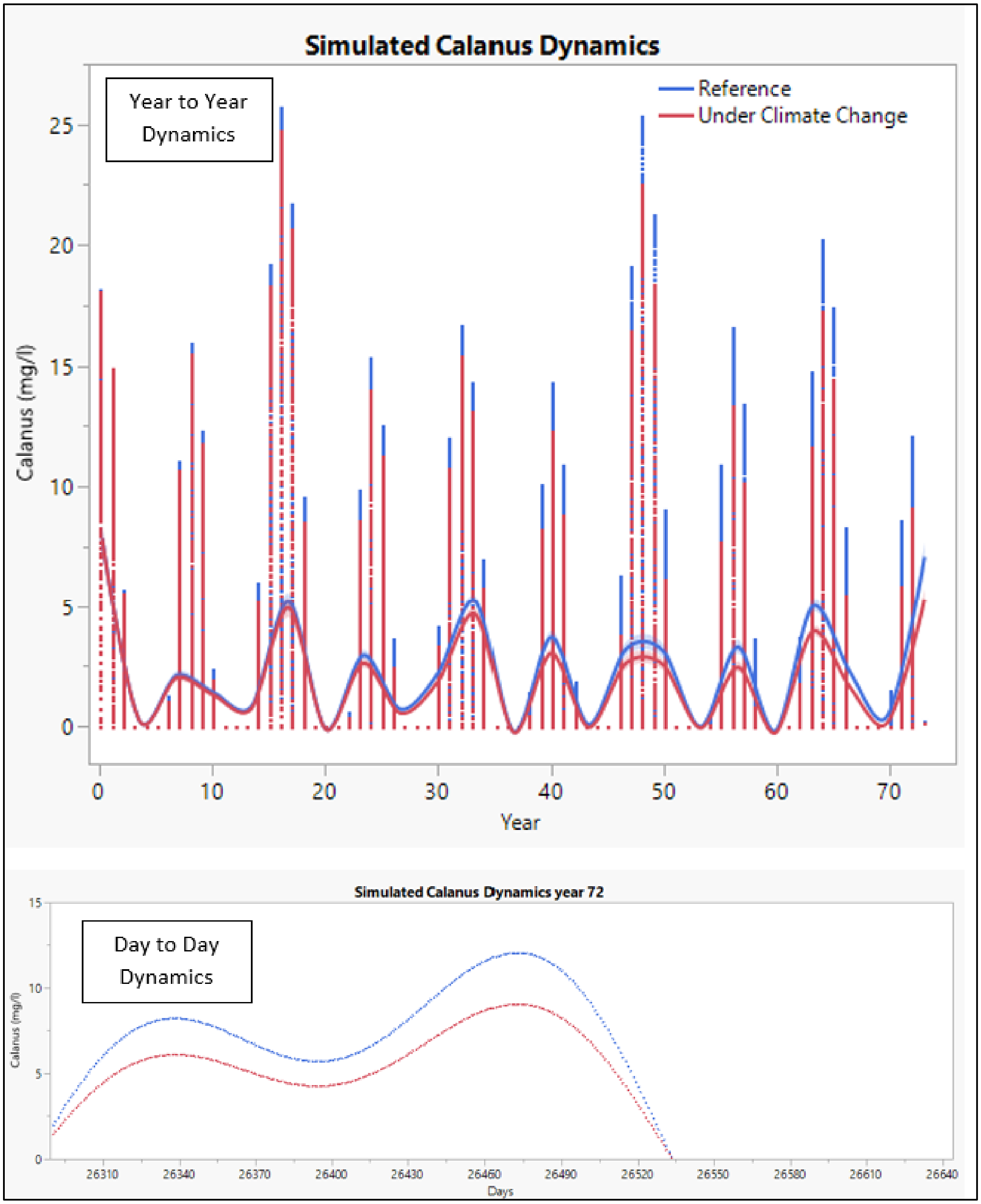

Figure A4. Simulated *Calanus* dynamics, assuming climate change effects on *Calanus spp.*, the major food source for sand lance.
Above: year to year dynamics; *below:* day to day dynamics

The sea surface temperature model facilitates the generation of SBT dynamics under assumptions of climate change at different locations:

$$SBT_l = max\ (4, ((N(\mu_m, \sigma_m^2) + DT + N(\mu_c, \sigma_c^2)) - dD_l)))$$

Equation 19

Where μ_m, σ_m^2 are the mean and standard deviation of the yearly averages and μ_c, σ_c^2 are the mean and standard deviation of climate-induced changes to sea surface temperatures. DT are daily deviations from the mean to add seasonal dynamics. D_l is the depth at location multiplied by d (decrees of °C cooler per meter of depth), shown in **Figure A5**.

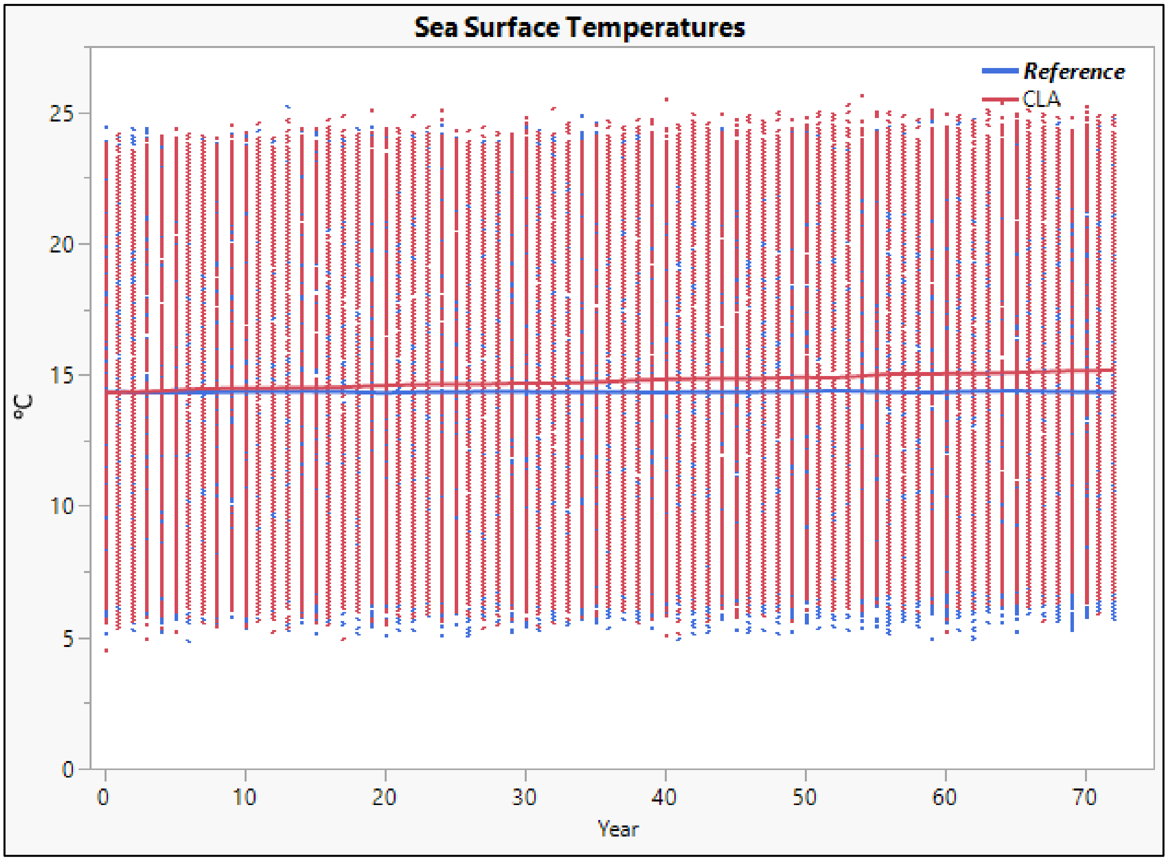

Figure A5. Climate Change A: assumed climate change effects on sea surface temperatures.

Climate Change B–Coastal Communities: Impacts via beach erosion are modeled using the increase in mean rate of or short-term erosion rates for beaches.

$$min\ (B, if(Yr > yr, EPR, LRR)$$

Equation 20

Where Yr is a counter of years into the simulation, yr is the year of choice when to change erosion rates from long-term trends (LRR) to short-term trends (EPR) in the model. Estimates for long $N(\mu_{LRR}, \sigma_{cLRR}^2)$ and short-term trends $N(\mu_{ERP}, \sigma_{EPR}^2)$ *in shoreline displacement* were sampled from Hapke et al. (2011) as the reference scenario and altered to represent a future change in the EPR due climate change. **Figure A6** shows the changes in sand simulated for 12 different beach locations on Long Beach Island (NJ).

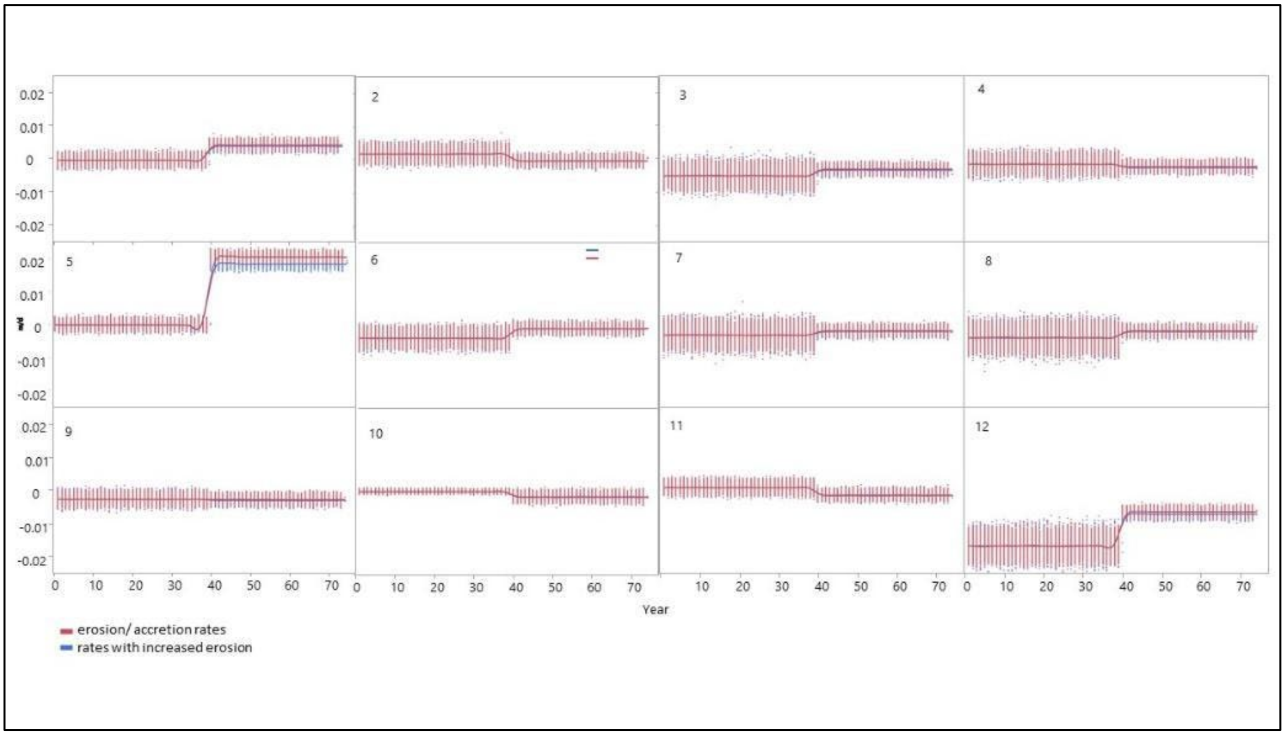

Figure A6. Changes in sand simulated for 12 different beach locations on Long Beach Island (NJ).

A.6 Spatial Models

Applying the unit models as nodes for spatial dynamic simulations involves the design of spatial representation of areas in extent and resolution so that databases can be built in assigning spatial parameters to locations. The unit model nodes are location dynamics exchanging matter through coupling. How locations exchange information requires additional code to the unit models. There were two specific regions that we simulated for a unique reason. A coastal region in New Jersey that had many requests for beach nourishment projects (NJ-MIMES) and Massachusetts Bay (SB-MIMES) where most data and knowledge about sand lance is being developed. The regions are shown in **Figure A7**.

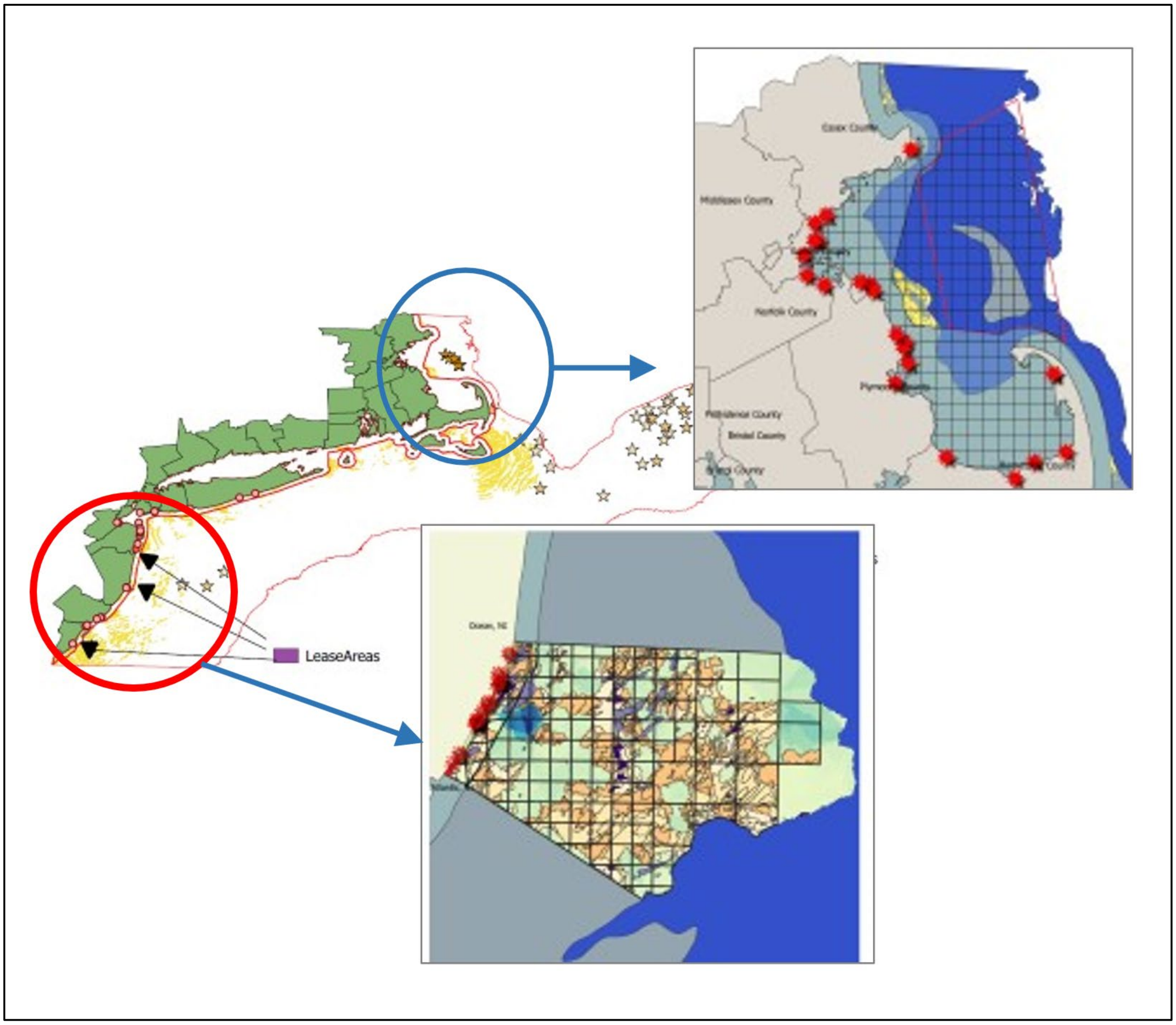

Figure A7. Locations and maps of the NJ and MA study areas.
The NJ-MIMES and SB-MIMES model extent and spatial unit resolution are shown by the square grids.

A.6.1 Beach Spatial Model

For NJ-MIMES, we characterized the 12 upland unit models by beach and urban areas. For SB-MIMES we characterized 61 areas. In estimating the beach areas, we used GIS data from 2 m above sea level contour to 5m below sea level to determine medium elevations and the slope, the TNC Soft Sediment map (Anderson et al. 2010) provided estimates for the type(s) of sand (grain size), and Hapke et al. (2010) provided short- and long-term erosion rates. *Beach profiles* published in the NJDEP 2016 report supplied initial and desired sand volumes (**Table A1**). Within these beach areas, we determined *where* renourishment happens, which further helped us delineate drivers of sand demand. For this, we identify renourishment projects in each unit model's beach area by overlaying previous or potential future sand projects from The West Carolina Beach nourishment database (https://beachnourishment.wcu.edu/). Those with previous projects also documented a motivation for the project; we assumed all were relevant except for those denoted as being for 'Navigation' (which is likely a sand removal project).

The beach model (**Figure A8**) is coded for coupling among beach locations and there is no exchange of either people, capital investment or beach sand to migrate between beach locations. The beaches relate to each other solely by their ranked urgencies (U) and assume limited resources and trade-offs between beaches on the importance of beach assets. While the model offers the tools to state these preferences to derive urgency, how these tools are parameterized and reflect decision-making is by no means based on credible research.

1. Sources of uncertainty:
    a) Grain size preference and existing and desired volume needed for beaches
    b) Projection of the rate at which beaches need renourishment into the future
    c) Overfill rates
    d) Potential mismatches on overlap with sand lance via grain preference and/or depth
    e) Impacts on sand lance in terms of mortality (direct death as well as indirect via turbidity) as well as on carrying capacity due to loss of sand
2. Impact on model and results: Differences in grain preferences and volume needed as well as overlaps with sand suitable for sand lance could shift where sand harvesting goes for sand, potentially changing overlaps with where sand lance are; more/less demand (including as altered by overfilling, rate of renourishment projects) for beach renourishment could increase/ reduce risks for sand lance as well as outcomes for the industry and coastal communities; impacts of sand dredging on sand lance can result in more/less sand lance.

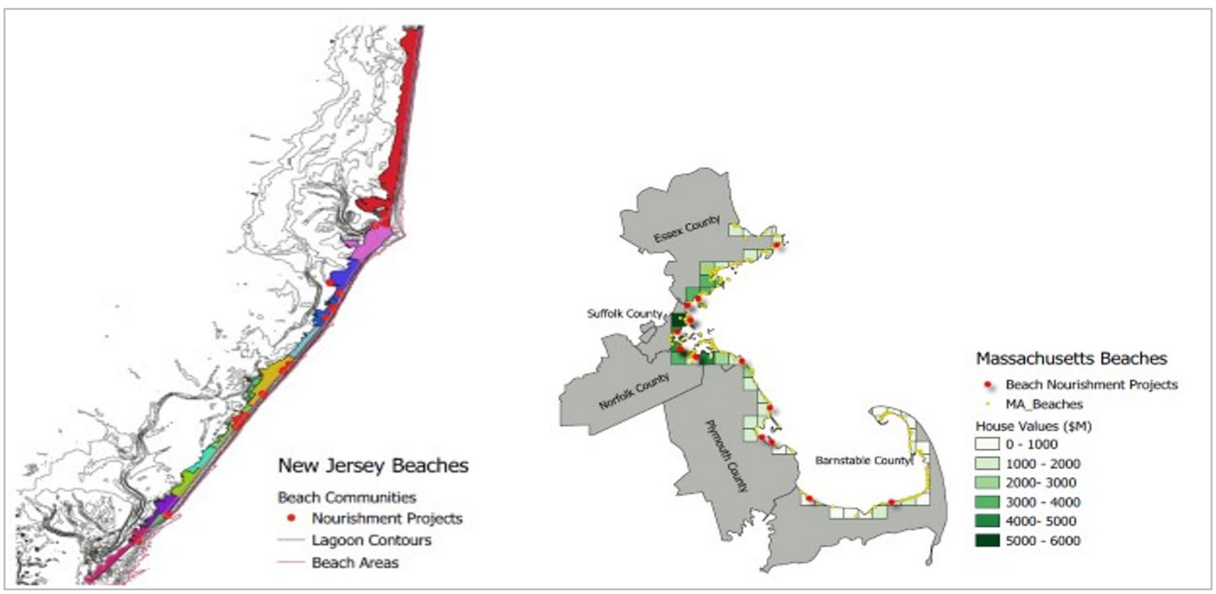

Figure A8. NJ-MIMES and SB-MIMES models.
The New Jersey beach model includes 12 communities on Long Beach Island delineated by US CENSUS Track groups. The Massachusetts beach model consists of 61 communities delineated by MIMES polygons and parameterized by US Census Block groups

A.6.2 Marine Spatial Model

For NJ-MIMES, we characterized 134 marine unit models roughly based on BOEM aliquots (https://coast.noaa.gov/digitalcoast/data/offshorecadastral.html) separating Federal from state waters. For SB_MIMES we characterized 299 based on the same criteria areas and made sure it included the SBNMS.

Designation of sand resources

We parameterized potential *borrow areas*, i.e., areas where sand will be harvested to address renourishment project needs in the marine unit models, on (1) water depth, (2) amount of sand, (3) type of sand (grain size), and (4) distance to renourishment projects on the coast.

Designation of sand lance habitats

It is important to carefully ascertain with data what constitutes critical sand lance habitats that we then reflect in both NJ-MIMES and SB-MIMES—that is, the same elements determine sand lance "hot spots" in reality and in the models. Initially, we hypothesized this would be a combination of sand grain size and water depth, and aligned with areas of high food for sand lance, in this case zooplankton and in particular *Calanus finmarchicus*, a key lipid-rich plankton species. We also know from field experience and discussions with our research team that physical characteristics, such as upwelling and oceanographic currents, are also important, but they are outside the scope of this contract; we aimed to find hot spot proxies from the data at hand and avoid involved oceanographic modeling. To evaluate our hypotheses and determine what characterizes sand lance habitat, we wanted to include as much information as possible, so did not limit this analysis to our study locations and instead looked across the entire seaboard from the Gulf of Maine to New Jersey where useful data could be found. We reasonably assumed any relationships found between sand lance and habitat across the region would be the same for our study locations, and this wide lens was necessary given the paucity of data in regions beyond Stellwagen Bank Sanctuary.

The marine spatial model facilitates coupling through the exchange of sand lance in the larval stage drifting in and out of locations (n) elaborating on the $Din_t^{1,i} - Dout_t^{1,i}$ dynamics in the unit model

$$Din_t^{2,n} = Dout_t^{2,n=neighbor} + Larvae\_from\_outside$$

$$Dout_t^{2,n} = \max(0, \text{Dispersion\_rt} * FBM_t^{2,n}) * Settlement_t$$

Equation 21

Larvae from the outside only enter through border cells and only under certain wind and current directions. The amount of larvae is proportional to larvae already in the system to mimic good and bad years. The dispensing rate to set the speed at which the larvae can travel between locations. Settlement sets the time restraint for when larvae are in the water column

A.7 Sources of Uncertainty

A.7.1 The Ecosystem

Inaccurate dispersal dynamics, lack of information on the water currents that direct larval dispersal, and estimates of suitable habitat will cause sand lance to emerge at model locations where they may not be observed in the study area. Imprecise dispersal rates will produce errors for the rate upon which sand lance populations can be reestablished in suitable habitats after a collapse.

Data in trawl surveys are inadequate for accurately representing sand lance distribution and abundance

The Eco Mon data lumps all plankton *spp* used, not just *Calanus*. No information is available on how much sand lance can exist per area (carrying capacity) and how sand dredging might impact this. Other missing elements to influence food availability are information on upwelling events and microhabitats.

Not included in the model are the food web feedbacks between the predators and prey populations. We use imprecise estimates for predation rates and estimates of presence for the various predator groups.

Impact on model and results: The scarcity of observation on sand lance presence hinders the model precision to render biomass estimates and where the model locates them is not very reliable. The lack of these data does not mean that the model is now inaccurate, but scenario outcomes need to be considered only relative to each other and calibrated against real-world observations.

Sand lance populations seem to be influenced more by bottom-up processes (the availability of *Calanus spp.* and the impact from winter mortality) than by the top-down processes of predation. There is the potential that shifts in the marine ecology will cause other feeder fish to invade to provide sustenance to predators in lean sand lance years (not modeled) in case top-down processes might gain more importance.

Observations on sand lance could be improved through specialized surveys, separating out *Calanus spp.* estimates from total zooplankton estimates, and consulting high-resolution ocean circulation models on upwelling dynamics.

A.7.2 Sand as a Resource

Imprecise estimates on the availability of sand in borrow areas due to missing data on the depth of suitable sand deposits depth (Assumed a uniform depth of 2m deep for each sand deposit). Lack of information on the properties required in each of the nourishment projects (color, size, rounding, etc.)

Impact on model and results: More/less sand can reduce/increase the potential for impacts on sand lance, both directly as well as indirectly (e.g., change in carrying capacity).

A.7.3 Beach Marine Spatial Dynamics

The coupling between the beach model and the marine model through the sand transported at the borrow areas and deposited on the beach contributes an estimate of the economic cost of a nourishment project as an important factor in the trade-off between ecological impacts and the security against flooding.

For NJ-MIMES and SB_MIMES we calculated the distances between beaches and marine locations to allow for sand sources in marine areas to be transported to the beaches. The project time (days that the dredge barges are in operation) and estimate of costs depends on the total amount sand that need to be sourced and the distance between the sand resource and the beach to be nourished, considering the sailing speed, hull capacity, time of loading and unloading capacity of the equipment available.

Rules set to engage in a nourishment project

Timing:

For the beach that is most urgent the following conditions need to be met:

1) Communities did have sufficient time to organize a nourishment project.

2) A dredge barge needs to be available.

3) There should not be any ecological and or weather concerns.

A.7.4 Sources of Uncertainty

Imprecise estimates on the availability of sand in borrow areas due to missing data on the depth of suitable sand deposits depth (assumed a uniform depth of 2m deep for each sand deposit). Lack of information on the properties required in each of the nourishment projects (color, size, rounding, etc.) can mean the sand harvesting industry will need to go to fewer/more places for sand, thus changing number of sand lance polygons potentially disrupted, as well as increasing/reducing efficiency of dredging and the time that beaches are in need of renourishment (exposure). Better matching of sand properties between what is needed on the beach and what is available in the marine environment will improve estimates on project costs.

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