Seagrass Sentinels: Predictive Distribution Modeling and Environmental Drivers of *Zostera marina* in Casco Bay, Maine

A thesis submitted by

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Abstract

Eelgrass (*Zostera marina*) is a critical component of coastal ecosystems, providing essential services such as habitat for marine species, nutrient cycling, and shoreline stabilization. Understanding the spatial and temporal distribution of eelgrass is vital for conservation and management efforts, particularly in the face of environmental changes. This study employs spatiotemporal modeling techniques to predict the distribution of eelgrass habitats in Casco Bay, Maine.

Using MaxEnt, a species distribution modeling tool, I incorporate variables such as temperature, salinity, dissolved oxygen, total nitrogen, turbidity, and bathymetry to generate a presence-only predictive model of the region. Spatial statistics, including Local Moran's I and Emerging Hotspot Analysis (EHSA), are utilized to identify and analyze patterns of eelgrass presence and distribution across different temporal periods.

This research contributes to the understanding of eelgrass ecology and provides a framework for predicting presence under varying environmental conditions. The findings can inform conservation strategies and management practices aimed at preserving and restoring eelgrass habitats in coastal Maine, ensuring their resilience in the face of climate change and anthropogenic pressures.

Acknowledgements

I would like to express my gratitude to my thesis advisor, Professor Sumeeta Srinivasan, whose guidance and geospatial expertise have been invaluable throughout this research journey. I am also grateful to my thesis reader, Professor Mary Davis, for her insights that significantly improved the quality of this thesis, including when this endeavor was still in its prospectus infancy. In addition, I'd like to thank Professors Shan Jiang, Christine Cousineau, and Kate Davies for being willing to brainstorm ideas with me — without their collective expertise, this project wouldn't have gotten off the ground. I would also like to extend my thanks to the Department of Urban and Environmental Policy and Planning at Tufts University. UEP's generous support has been instrumental in my academic growth and professional development, and I am glad to call Brown House and Bromfield-Pearson my graduate homes.

Special thanks go to Dr. Janelle Goeke of the Casco Bay Estuary Partnership for providing me with guidance on predictive species modeling as well as crucial environmental datasets from CBEP and Friends of Casco Bay, which made this entire study possible. I am also thankful for Team Zostera from COBALT, a Portland-based citizen science initiative, for connecting me with like-minded academics and researchers. Thank you all for taking the mission of protecting and conserving eelgrass in coastal Maine so rigorously and for providing the resources for early-career researchers to succeed.

Another round of thanks goes to the Tisch Data Lab for creating a productive learning environment for me to gain the skills needed to carry out this study. Shoutout to Carolyn Talmadge, Kyle Monahan, Uku-Kaspar Uustalu and the rest of the TTS team for making this space what it means to me. To my fellow Data Lab denizens, I can't wait to see what you all do in the world of mapping. I am also thankful for the Data Intensive Studies Center and Professor Abani Patra for fostering a collaborative environment where I was able to provide regular updates on my thesis topic as a research assistant. This was key to keeping me on track to graduate, and the camaraderie with fellow DISCers has been both inspiring and motivating.

To my friends, thank you for your support and for being a source of encouragement and levity throughout these past two years. To my partner, Derek, your kindness and understanding has been an unwavering constant throughout this journey — as two West Coasters who met in Berkeley over half a decade ago, we've come a long way (and so has our Subaru!)

Finally, to my family, thank you for your unconditional love and belief in me, which I am so lucky to have. Your support, interest in my work, and encouragement has been the foundation upon which I have built my academic and personal achievements. This thesis is for you.

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Chapter 1: Introduction

This thesis investigates the distribution of seagrass (*Zostera marina*) in Casco Bay, Maine. Seagrass meadows play a crucial role in the ecosystem by serving as a habitat for juvenile fish species, preventing shoreline erosion from root anchorage and dampening wave energy, and perhaps most importantly, serve as one of the world's major carbon sinks. Seagrass (also known as eelgrass) stores organic carbon in its peat and biomass, preventing CO2 from entering the atmosphere.

Seagrass has been relatively under-studied in the pantheon of scientific inquiries, but it has also had its share of fans. Erasmus Darwin, the father of Charles, dedicated a stanza of a poem to the seagrass:

""Stretch'd on her mossy couch, in trackless deeps,

Queen of the coral groves, Zostera sleeps;

The silvery sea-weed matted round her bed,

And distant surges murmuring o'er her head."

– Botanic Garden (Part V), Erasmus Darwin, 1803

The impact of urbanization was recognized to be a significant threat to seagrass by the turn of the 21st century. In the seminal textbook *Seagrasses: Biology, Ecology and Conservation* by Larkum, Orth and Duarte in 2006, the authors echo concerns raised by earlier researchers such as C. den Hartog regarding the pivotal role seagrass appeared to play in nearshore ecosystem functions and what would happen with their continued decline (Seagrasses of the World, 1970).

Seagrasses are also threatened by agricultural pollution, invasive species, and rising sea temperatures. The focus of this thesis is on Casco Bay because it is the heart of industrial activity in Maine and comprises several historically important cities, including Portland, Freeport, and Brunswick.

Research Questions

In this thesis, the following questions are posed:

- Using geospatial analysis, what is the extent and distribution of active seagrass beds in Casco Bay, Maine?
- What does the restoration potential of these seagrass meadows represent for the state?

Chapter 2: Literature Review

Through this literature review, I will first explore the various facets of seagrass ecology to establish a foundational understanding of this critical marine ecosystem. The initial section will delve into the biology, distribution, and ecological roles of seagrasses, highlighting their significance in coastal environments. By examining the life cycle, growth patterns, and interactions with other marine species, this section aims to provide a comprehensive overview of seagrass ecology.

The subsequent section focuses on the importance of seagrass for future climate resilience in Maine. I will review recent studies that emphasize the role of seagrasses in carbon sequestration, shoreline protection, and as a buffer against the impacts of climate change. This part of the chapter will synthesize research findings that underline the potential of seagrass meadows to mitigate climate-related challenges and support coastal resilience in Maine.

Finally, the chapter examines studies utilizing ArcGIS and predictive spatial ecological modeling, specifically the MaxEnt model, to identify likely locations for eelgrass beds that warrant policymaker's attention and protection. By analyzing methodologies and outcomes from various research efforts, potential habitats can be mapped, and conservation strategies identified. The aim is to illustrate the advancements in technology that aid in the sustainable management of eelgrass ecosystems, which are a crucial blue carbon resource.

Seagrass Ecology

Broadly, seagrasses are one of the three primary carbon sinks in the ocean, alongside mangrove reefs and tidal marshes. They were first classified under this name by the scientist

Ascherson (1871), although they had long been known to coastal farmers, fishers, and inhabitants as a source of insulation, fertilizer, roofing material, and of course, as weaving material. They are the only flowering plants found in the marine environment and are typically located in coastal or nearshore environments and form dense meadows or beds that serve as important marine habitats. To the visible eye, blades of seagrass resemble their terrestrial counterparts but retain greater complexity – four defining characteristics are that they are purely marine organisms, require a soft substrate for rooting, immersion in salt water, and need sufficient irradiance for growth (Zimmerman, 2006).

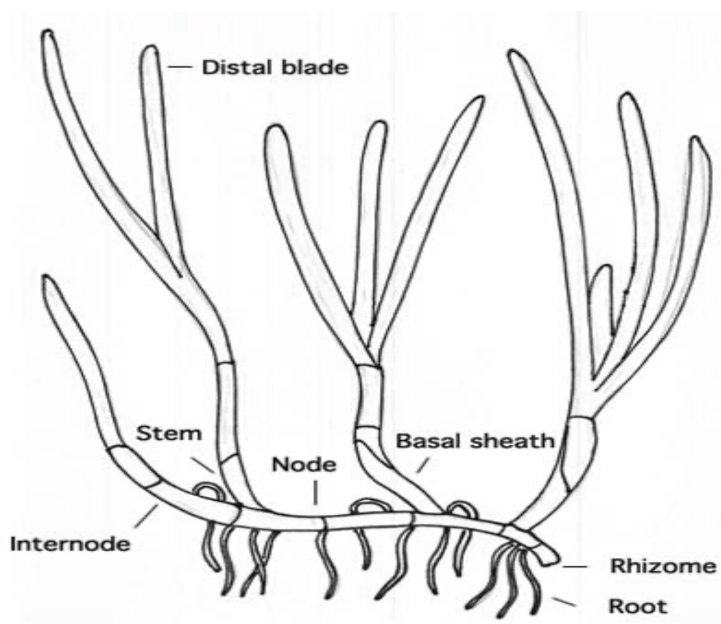

Figure 1: Seagrass schematic (Friday Harbor Labs, University of Washington, n.d.)

Based on the diagram above (Figure 1), a cursory overview of seagrass morphology will prove handy in understanding why various shifts in ocean mechanics, solar irradiance, and invasive species can pose a problem – as well as explain how this species has thrived over the millennia.

Seagrasses have rhizomes that extend beneath the substrate and are uniformly thin. The rhizomes contain large spaces, or lacunae, that influence air pressure during photosynthesis (Hemminga and Duarte, 2000). Notably, the rhizome also provides structural support for the plant and stores nutrients. Extending from underneath the rhizome are narrow roots. The expansion of seagrass meadows is achieved through self–propagation via meristematic cells within each node, allowing it to grow horizontally – sections between nodes are thus called internodes (Smith, 2008). The most familiar parts of the plant are likely the stem and distal blade, which are numerous and rise above the substrate, and occasionally, the surface of the water (Figure 2). Water vapor transpiration and gaseous transfer occurs through these green blades, as does photosynthesis (Kuo and Hartog, 2006). One can imagine seagrass as a plant that grows horizontally, forming beds or meadows, and upwards.

Asexual reproduction, as described in the horizontal clonal growth above, is not the only way seagrass can propagate. They also are capable of reproduction akin to their terrestrial cousins, with male seagrass flowers releasing pollen from their stamens, which are carried along by water currents until they encounter a female pistil. The fertilized seagrass form seeds that can be buoyed for long distances before germinating on sandy bottom (Reynolds, 2018). If small marine animals, such as crustaceans, inadvertently track seagrass pollen or seed along, this can assist in their dispersion and contribute to greater genetic variation.

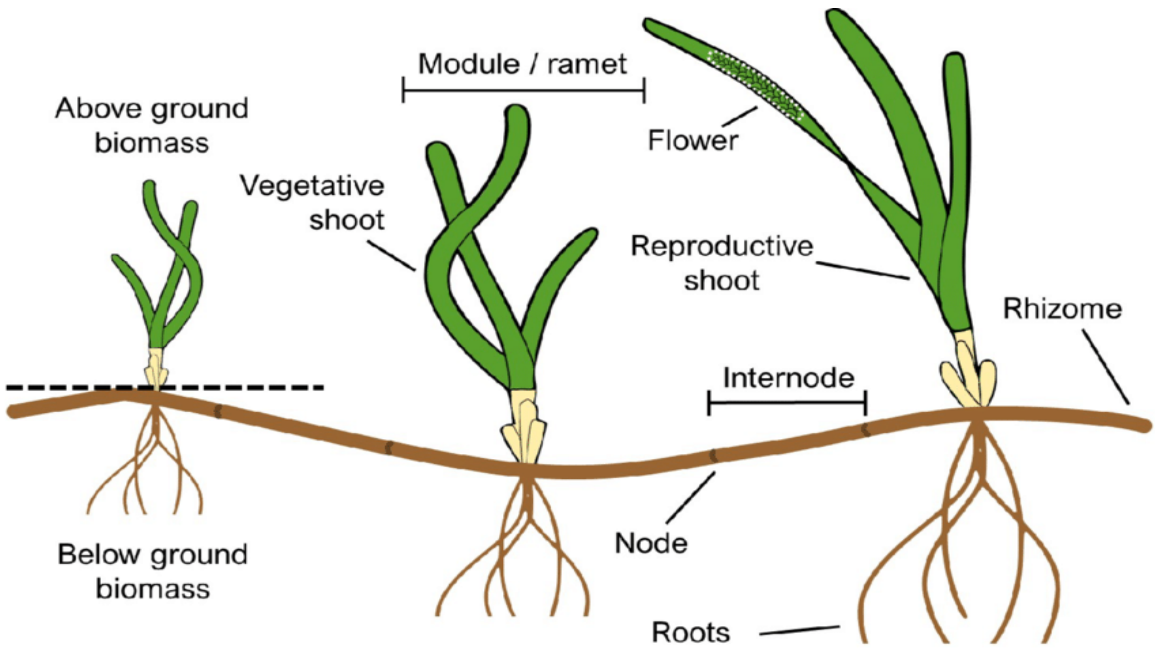

Figure 2: Zostera marina morphology. (Source: Howarth, et al. 2021)

There are over 70 species of seagrasses and three primary genera, but in this thesis *Zostera marina* will be examined. This common species of seagrass is distributed along shallow coastal waters along both the Pacific and Atlantic, from Baja California through Alaska and the entire Eastern Seaboard of the United States, surrounding Japan and East Asia, as well as around Western and Northern Europe (Figures 3 and 4).

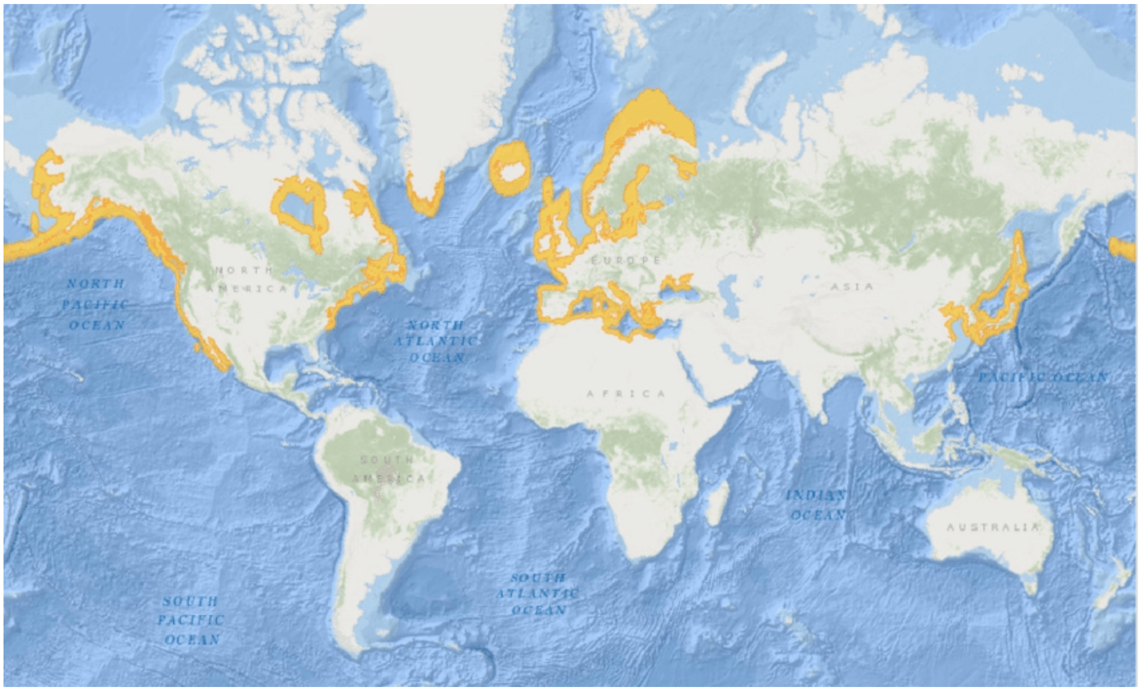

Figure 3: Spatial distribution of *Zostera marina*. Locations in yellow indicate presence. (Source: Gundersen, et al. 2021).

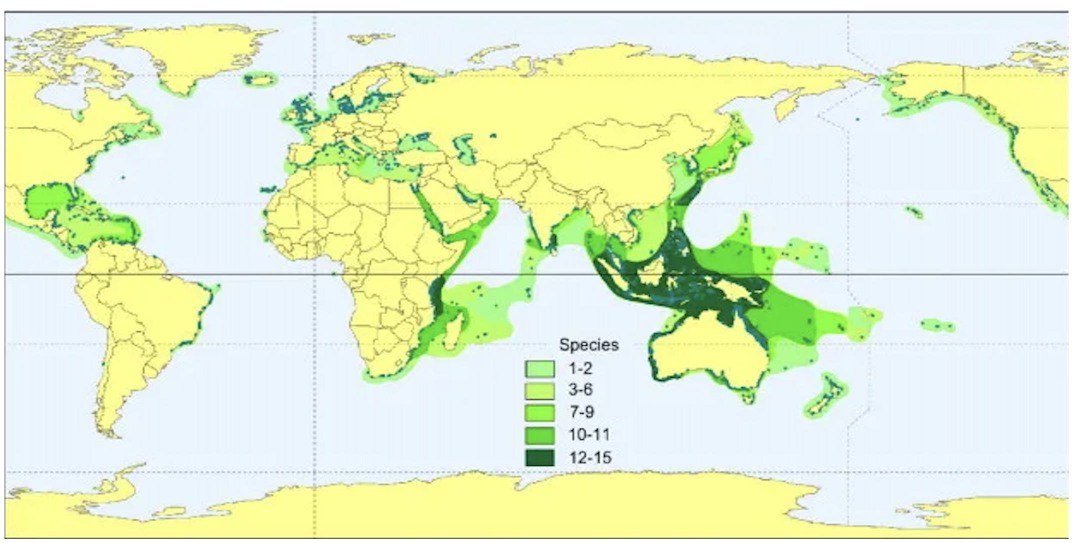

Figure 4: Seagrass spatial distribution showing the number of species at each site. (Source: Short, et al. 2007)

Ecosystem Services

Seagrasses can absorb CO_2 at rates up to 35 times faster than rainforests (World Wildlife Fund, n.d.), and draw carbon dioxide from water to store in soil or mud, where the gas can remain indefinitely if undisturbed. To put their importance in other words, seagrass covers merely 0.1% of the ocean but provides 18% of its carbon storage, per a 2020 United Nations Environmental Programme press release. The CO_2 sequestration of seagrass globally has been estimated to exceed 80 million metric tons per year (Howard, et al. 2017). The paper noted an acre of seagrass could potentially store 740 pounds of carbon per year, an amount equal to a vehicle traveling almost 3,900 miles (about 6,300 km).

Seagrass ecosystems go further than carbon sequestration when it comes to their overall importance – they also play a crucial role in preventing shoreline erosion during inclement weather and serve as a valuable habitat for a variety of marine species, such as juvenile fish and bivalves. They are also capable of providing a source of refuge for larger animals ranging from octopi to manatees, which may even eat the leaves directly for food (Reynolds, 2018). These meadows are also important for slowing water flow to capture silty particles and anchoring sediment. In fact, they can serve as an oceanic nutrient pump by releasing nutrients absorbed from their roots back into the water (Reynolds, 2018).

The importance of seagrass to ecosystem services has been recognized around the world. The International Union for the Conservation of Nature (IUCN) has a dedicated Seagrass Specialist Group that consists of a global membership of biologists and the Smithsonian Institution hosts a similar monitoring network called SeagrassNet, which has been operating continuously since 2001. From SeagrassNet, participant countries and bioregions include Australia, Canada, Colombia, Denmark, Malaysia, Mexico, Micronesia, the United Kingdom, the United States, Tanzania, and Vietnam (SeagrassNet, n.d.). This network mirrors the coverage and quantities of seagrass species around the world (Figure 4).

Major news outlets, including the Guardian (Brown, 2023) and New York Times (Schlossberg, 2023), have also expounded on the plant's importance regarding the climate crisis. "Anchored on the shorelines of every continent except Antarctica, these plants (and they are plants, not algae, that sprout, flower, fruit and go to seed) are one of the most powerful but unheralded climate solutions that already exist on the planet."

Figure 5: Eelgrass meadow in Northern Europe. (Source: DHI Water & Environment, 2019)

Revisiting their morphology, much of what they offer to the marine world manifests in the form of their spatial arrangement, which expands both vertically as well as horizontally to form intricate beds (Phillips and Milchakova, 2003). This functionally provides four habitats to inhabit – on the seagrass blades itself, among the seagrass meadow (Figure 5), on the surface of the peat substrate, and burrowed within (Stauffer, 1973). If this network is undisturbed, they can provide food and shelter and nursery ground for a variety of species.

It can be argued that coastal resilience depends on naturally occurring solutions like seagrass, whose importance ranges from being crucial carbon sinks to providing valuable ecosystems solutions. In fact, seagrass protection can meaningfully contribute to 16 of the 17 United Nation Sustainable Development Goals (Unsworth, et al. 2022) through Sustainable Cities, Responsible Consumption, and Life Below Water, to name a few. To take a different tack on why seagrass conservation is critical, because of their role as a carbon sink, their degradation and eventual destruction by anthropogenic activities means more than collective guilt to shoulder –they will release carbon into the atmosphere and worsen the ongoing climate crisis.

There are various steps that can be taken to address ongoing seagrass degradation. Environmental restoration tends to remain on the local scale, as there are no laws that govern the management of the plant on a broader scope.

GIS Applications

Habitat suitability models in ArcGIS Pro have demonstrated excellent applications for seagrass in sites around the world. A baseline reference of species occurrence data and input variables that represent factors that contribute to or inhibit productivity are needed (Bittner, et al. 2020). However, the software is capable of handling the rest, given appropriate tasks and commands, such as running a linear regression model on raster data. According to a meta-analysis of seagrass habitat modeling, the most common variables utilized as inputs were sea surface temperature, bathymetry, light availability, and salinity (Bertelli, et al. 2022). Substrate type and wave energy were also utilized in some studies.

Sea temperature and salinity are crucial to *Zostera marina's* survival. As seagrass in Maine is found in coastal estuarine and marine habitats, the fluctuation of freshwater from rivers can affect their growth and development. According to a Danish study, low salinity – defined as between 2.5 and 5% – negatively affected the ability of eelgrass in a controlled environment to grow elongated shoots, photosynthesize and spawn (Nejrup and Pedersen, 2006). Salinity levels between 10% and 25% were deemed optimal. Sea water temperature can also be too hot or cold, although the former was more harmful and led to eelgrass die-off by a factor of twelve and decreased the rate of photosynthesis by 50% (Nejrup and Pedersen, 2006). The researchers determined that 10 to 20 degrees Celsius, or 50 to 68 degrees Fahrenheit, was optimal for growth and survival.

Other factors are not so cut and dry. Light attenuation, which is crucial to eelgrass survival, can be affected by the presence of sediment in the water column or macroalgaes (Simpson and

Dahl, 2017). As with any other plant, if light cannot sufficiently reach an eelgrass meadow or bed, it will struggle to survive. In fact, eelgrasses require more light due to the respiratory demand of their root structures (Goodman, et al. 1995). Generally speaking, most eelgrass meadows and submerged aquatic vegetation (SAV) can be found where light attenuation is between 10 to 30% (Kemp, et al. 2004). Other factors may also have varying impacts. For example, nutrient loading from agricultural or waste runoff can help seagrass meadows grow to a certain extent, but the cloudiness of the water and contribution to algal growth may then cause the meadows to struggle (van den Heuvel, 2019). This is one theory that is hypothesized for why eelgrass meadows appeared to abruptly blossom in Casco Bay in 2018. The third function was helpful in yielding interaction variables that indicated how the different covariates (e.g., salinity and turbidity, in this study) may have influenced each other.

Chapter 3: Data, Methods, and Context

In this chapter, I describe the data and methods used in the thesis and the study location where they were applied.

Data Table

Variable Name	Source	Year	Format
Casco Bay Eelgrass Coverage	State of Maine Geolibrary	2013, 2018, 2022	Polygon
Temperature	Friends of Casco Bay	2022	Attribute Table (Points)
Salinity	Friends of Casco Bay	2022	Attribute Table (Points)
Dissolved Oxygen (O2)	Friends of Casco Bay	2022	Attribute Table (Points)
Total Nitrogen (TN)	Friends of Casco Bay	2022	Attribute Table (Points)
Turbidity	Friends of Casco Bay	2022	Attribute Table (Points)
Bathymetric Contours	State of Maine (C. Halsted)	2019	Lines
Gulf of Maine / Georges Bank Area	National Oceanic and Atmospheric Administration	2015	Polygon

Table 1: Data Sources and Description

This work built off a Maine DEP report which analyzed the changes in seagrass coverage between 2010, 2013 and 2018 (Barker, 2018). It also provides further context to a 2023

Normandeau Associates report prepared for the State of Maine, which continued Barker's study and analyzed the 2022 seagrass cover using an aerial photography and field survey approach — incorporating geospatial predictive modeling can help subsequent seagrass studies determine the presence or absence of such meadows in Casco Bay.

Bathymetry data (BATHYM100) came from the State of Maine in the form of coastal bathymetry lines at a scale of 1:100,000 in 10-meter intervals. These contour lines were converted to raster data through ArcGIS Pro's Topo to Raster geoprocessing tool.

Methods

This analysis combined a quantitative and GIS approach with a literature review on eelgrass ecology and morphology. Geospatial methods were employed to analyze the current "state of seagrass" in Casco Bay. Geographic Information Science (GIS) refers to digital mapping that allows data to be associated with places and is widely used for natural resource management purposes (Audubon International, 2019). ESRI's ArcGIS Pro software was used to visualize spatial data and for spatial statistics as well as for species modeling using the MaxEnt model.

Local Moran's I and emerging hot spot analysis were utilized to understand the spatial patterns and clusters of eelgrass presence and health. Local Moran's I helps to identify areas of significant spatial autocorrelation, revealing clusters of high or low eelgrass density that may indicate underlying environmental or anthropogenic factors. In ArcGIS Pro, high-high clusters are indicated in light red, high-low outliers are in dark red, low-high outliers are in dark blue, and low-

low clusters are in light blue. Emerging hot spot analysis further highlights regions where eelgrass populations are either increasing or declining over time, providing insights into temporal trends and potential areas of concern or success in conservation efforts.

Within ArcGIS Pro, there is also a tool called Maximum Entropy (MaxEnt) that is useful for spatial habitat suitability modeling. The original author of MaxEnt is Stephen Phillips, a researcher at the American Museum of Natural History and Princeton University, who wrote two seminal papers on applying this machine learning approach to species distribution modeling (Phillips, 2006 and 2008). The model estimates the relationships between contributing environmental variables, or covariates, and the likelihood of presence, resulting in a continuous map that represents the probability of said species occurring in a specific location. In ArcGIS, the MaxEnt feature defaults to a map with 0-25%, 25-50%, 50-75% and 75-100% in terms of predictive modeling output.

MaxEnt creates a probability distribution for the species or variable of interest across the study area by finding the distribution that maximizes entropy, subject to the constraints created by the input data (Phillips, 2006). The premise of the model is fairly simple and requires just presence-only data – where confirmed observations of the species in question has been spatially recorded – and environmental variables, or covariates, which can influence the distribution of said species. Some common covariates include temperature, precipitation, soil type, and elevation. The model's output is logistic and ranges from 0 to 1, with 0 being a low probability of presence and 1 being very likely.

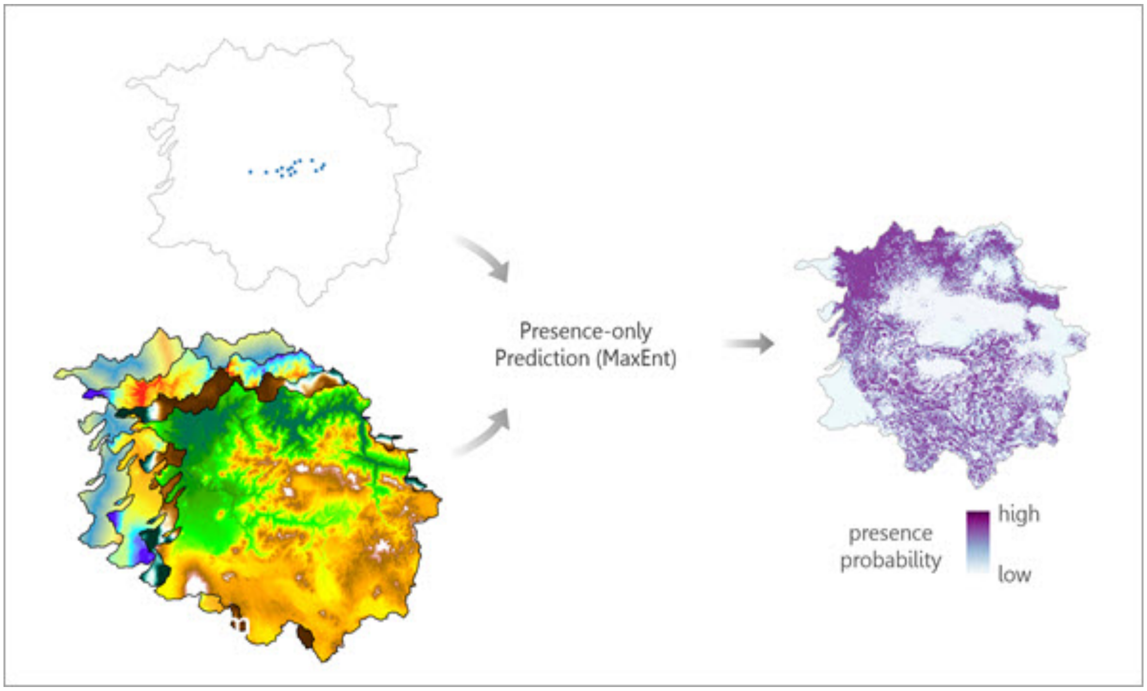

Figure 6: Example of MaxEnt model and required inputs. (Source: ESRI, n.d.)

I primarily obtained eelgrass coverage data from MaineDEP for the years 2013, 2018, and 2022. I accessed this data from a portal hosted by ESRI and maintained by the Maine Department of Environmental Protection. By using methods such as emerging hotspot analyses and spatial clustering, I identified patterns in seagrass meadow growth or decline. This data was used both for the exploratory spatial data analysis as well as the MaxEnt model.

For the MaxEnt model, I analyzed six covariates – temperature, salinity, dissolved oxygen, bathymetry, turbidity and total nitrogen (Figure 6). Empirical Bayesian Kriging (EBK) interpolation was used to generate rasters because it is suitable for larger areas and accounts for errors in estimating semivariograms. EBK is a geostatistical interpolation technique that is particularly useful for creating smooth and reliable spatial predictions from individual data points — in my case, the Friends of Casco Bay monitoring stations. When used for MaxEnt covariates, this approach helps to generate continuous surfaces of environmental variables that can improve the accuracy and reliability of species distribution models. All covariate data except bathymetry was from the Friends of Casco Bay (FOCB), a local Maine nonprofit focusing on protecting and understanding the Casco Bay watershed. FOCB has a series of monitoring stations placed around the Portland and greater Casco Bay region, which collect this data on a continuous basis. For the sake of consistency, I chose to use data points from the first week of June 2022 for all FOCB variables.

These MaxEnt outcomes may be included in existing integrated frameworks on how best to understand seagrass in Maine from a geospatial perspective, depending on their accuracy. For instance, they can be included in conservation planning techniques on identifying priority areas for seagrass protection, ecological corridors, and areas of high conservation value.

Study Context of Maine

Casco Bay is located in southern coastal Maine and is a major commercial, recreational and environmental hub for the state. A quarter of the state's population resides within the boundaries of the greater Casco Bay watershed (Casco Bay Estuary Partnership, n.d.) and nearby institutes of higher education include the University of Southern Maine and Bowdoin College.

The Gulf of Maine is warming more quickly than almost any other body of water in the global ocean. According to the Gulf of Maine Research Institute, the Gulf experienced record-breaking sea surface temperatures in 2021 and 2022. While 2023 did not set a new high, it was still two degrees Fahrenheit above normal. Shifts in two major ocean currents appear to be behind these changes. As the Gulf Stream current strengthens and draws additional warm water into the Gulf of Maine, the weakening Labrador Current flowing from the Arctic does not balance out the former as it did before (GMRI, 2023). This contributes to habitat suitability issues for sensitive species like *Zostera marina*, which may not be adapted to rising temperatures. Compounding the issue may be how the Gulf of Maine contains unique topography described by GMRI researchers as "a bathtub…with a deep center and shallow boundaries", making these temperature changes starker than they otherwise may have been as hotter waters cannot easily escape. Seagrasses are not the only species affected – cod stocks have also dropped precipitously in the region due to climate change (Pershing, 2015).

More than 50% of seagrass beds in Casco Bay have been lost in the last decade alone, making their decline staggering (Friends of Casco Bay, 2023). Warming waters, invasive species, agricultural runoff, and algal blooms have all contributed to these losses. Because seagrass meadows can take more than five years to propagate and have relatively low survival rates from existing restoration efforts (The Guardian, 2021), it is imperative to protect these existing ecosystems. According to the Middlebury Institute for International Studies, the seafood industry in Maine was valued at $3.2 billion in 2023. A decline in seagrass could threaten not just environmental stability, but economic growth, due to the numerous fisheries benefits the plant provides. To this end, they are particularly valuable to coastal communities as fishing grounds, ranging from intertidal to deep enough for watercraft (Nordlund, et al. 2017).

A recent report from the U.S. Environmental Protection Agency, Region 1 analyzed blue carbon reservoirs from New York to northern New England, representing a collected effort to understand the carbon sequestration potential and state of vegetated aquatic habitats in the region. Maine had the highest concentration of seagrass at approximately 21,700 acres, highest among the five states with Atlantic coastlines (Colarusso, et al. 2023).

Zostera marina is capable of sequestering carbon primarily in two ways: one, by uptake of carbon dioxide into plant tissue through photosynthesis, and two, the decaying of plant tissue into peatlands beneath the seagrass beds, where it can remain indefinitely. Per the U.S. EPA, most eelgrass carbon sequestration occurs via the second pathway (Colarusso, et al. 2023).

Much of the information gleaned from the report is available on the Northeast Ocean Data Portal, a publicly accessible, expert-reviewed geographic dataset on ocean ecosystems and the blue economy for coastal management and education purposes. This valuable resource was leveraged heavily when conducting predictive spatial distribution modeling in ArcGIS Pro.

Chapter 4: Results

This chapter will present the results of the GIS and spatial analysis. The first section will include ESDA (Exploratory Spatial Data Analysis), and the second section will include the MaxEnt predictive model of eelgrass in Casco Bay.

Exploratory Spatial Data Analysis

As part of an exploratory spatial data analysis (ESDA), Local Moran's I, Optimized Hotspot Analysis, and Emerging Hotspot Analysis were conducted. To begin, the 2013, 2018, and 2022 seagrass layers were converted to point data from vector polygons (ArcGIS Pro's Feature to Point Tool) and reprojected to the UTM 19N coordinate system. The original MaineDEP data is depicted in Figure 7 as a series of polygons, with 2013 data in light blue, 2018 data in light green, and 2022 data in pale red. This allowed for a visual overview of seagrass distribution over each half decade, an approach also taken separately as seen in Figures 8, 9, and 10. Converting this polygon data to points and depicting them per study year was intended to demonstrate changes in where eelgrass meadows were found and whether they had meaningfully shifted.

Figure 9 indicates eelgrass coverage for the year 2013, per MaineDEP. Figure 10 indicates eelgrass coverage for the year 2018, and Figure 11 indicates eelgrass coverage for the year 2022.

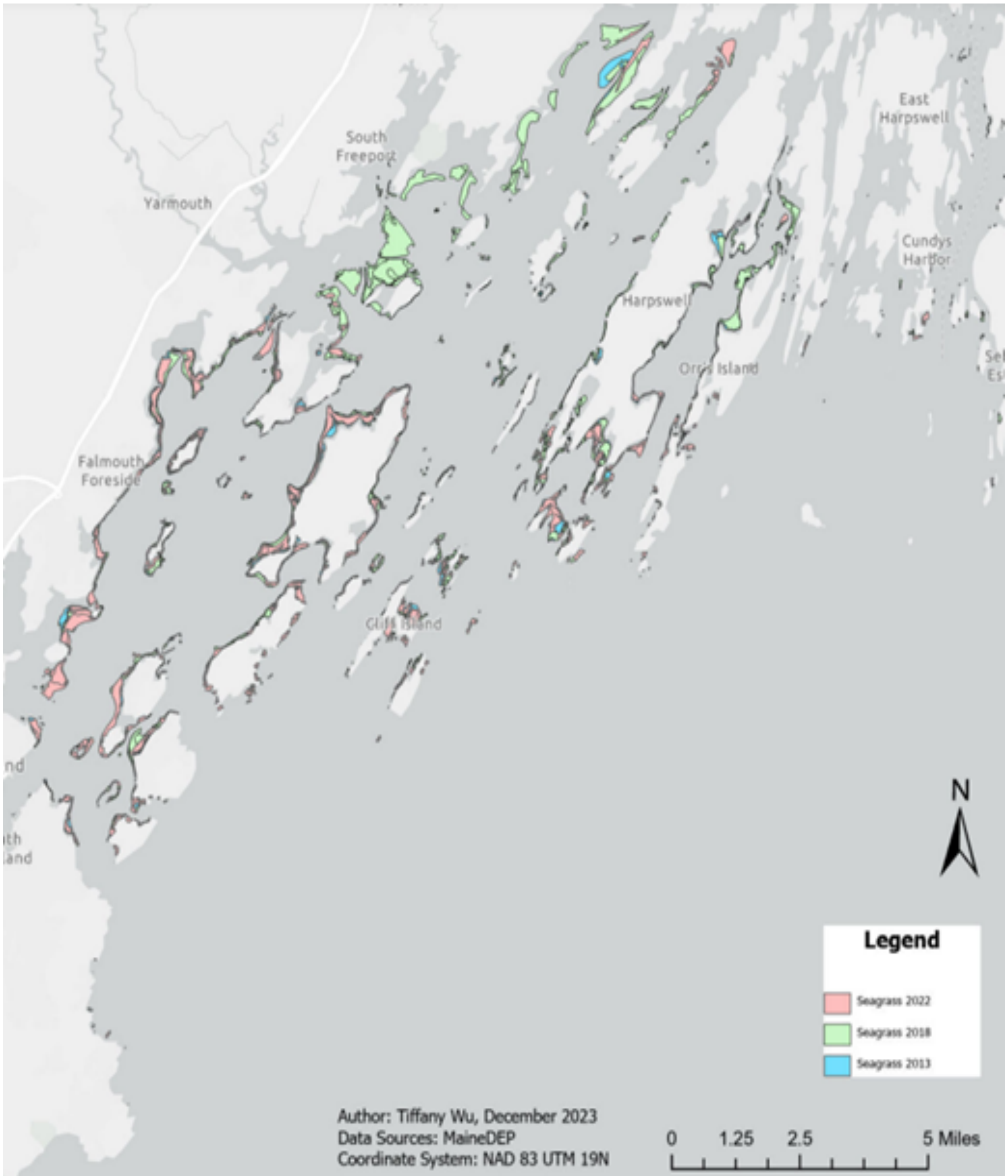

Figure 7: Original seagrass coverage for survey years 2013, 2018, and 2022.

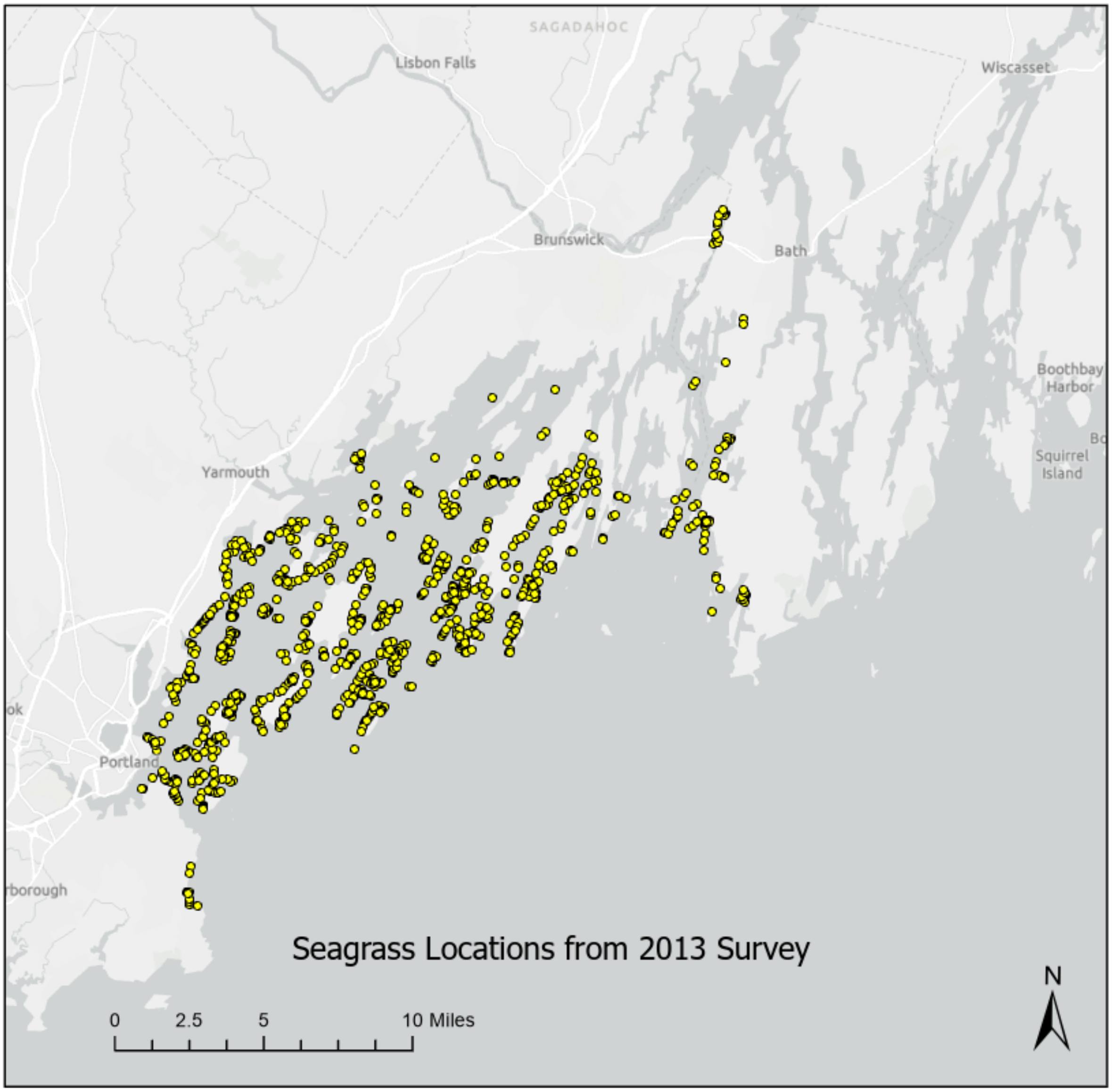

Figure 8: Seagrass Locations from 2013 Survey. (Source: Author)

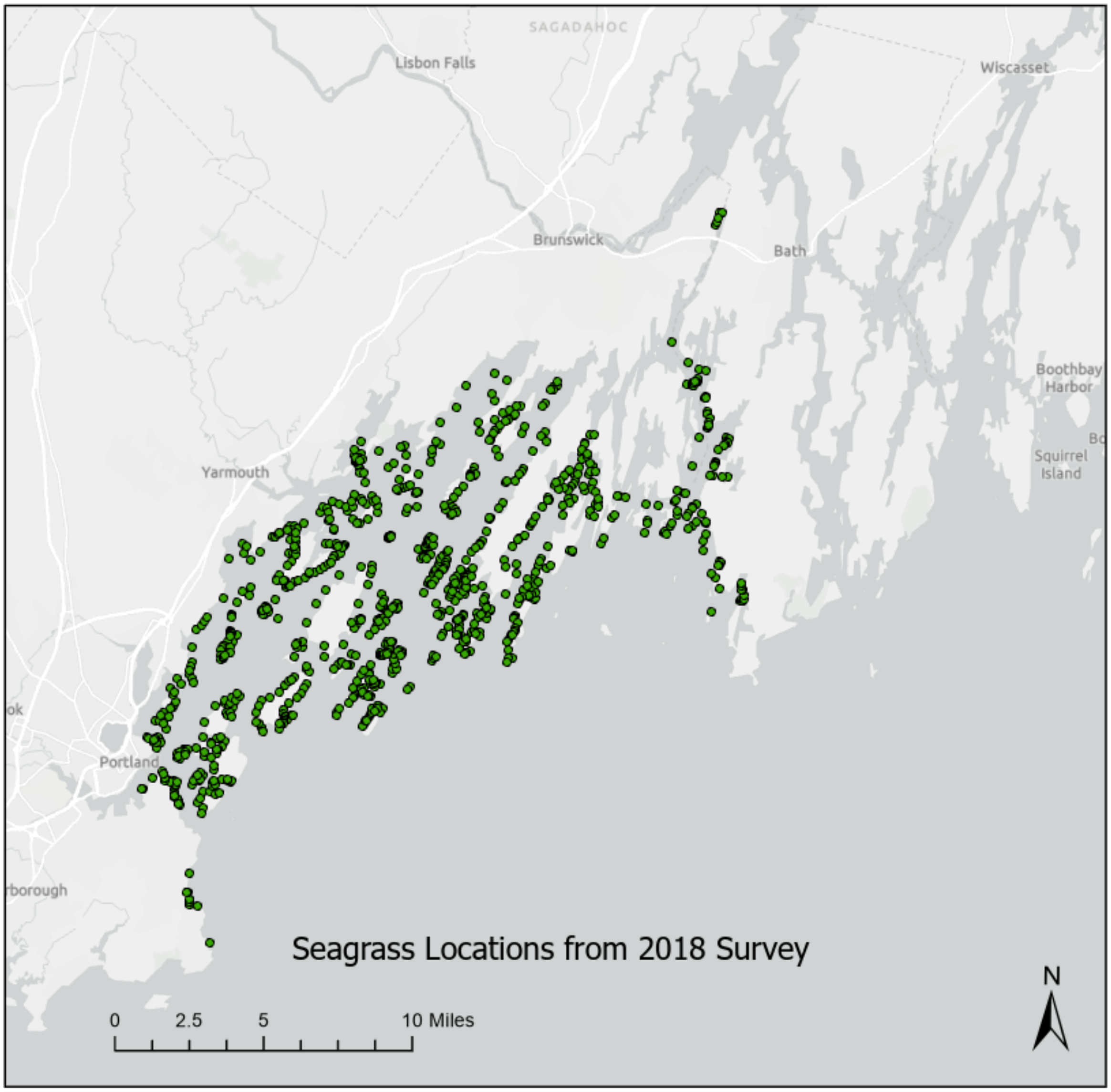

Figure 9: Seagrass Locations from 2018 Survey. (Source: Author)

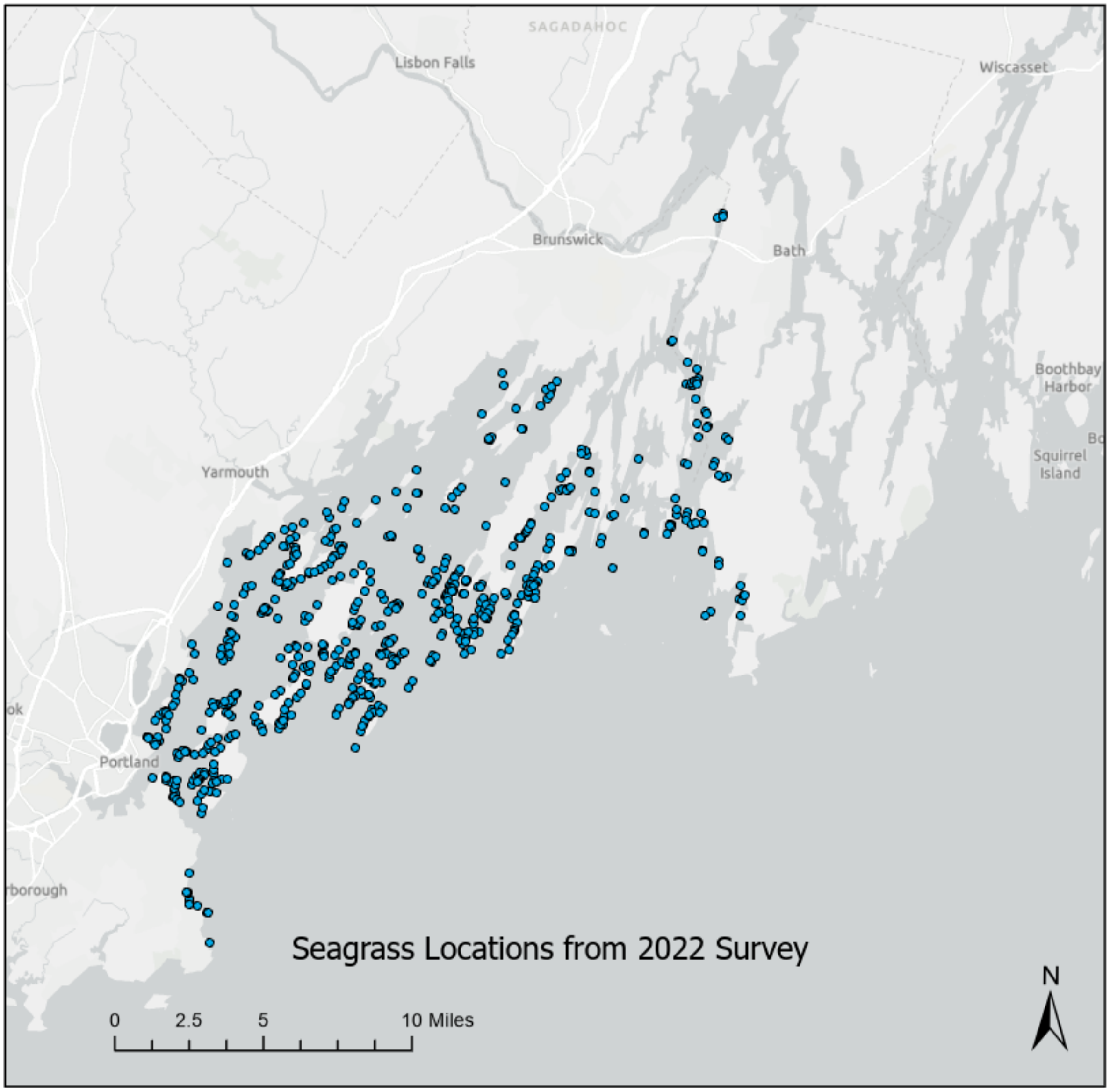

Figure 10: Seagrass Locations from 2022 Survey. (Source: Author)

Local Moran's I

In Casco Bay, it appeared that the only prominent high-high cluster in 2013 was just northeast of Portland, by Mackworth Island (Figure 11). The remainder of the high-high clusters were around Great Diamond Island and Peaks Island, the two islands directly east of Portland and south of the Harpswell coastline. High-low outliers were found a few miles north off Falmouth and on Great Chebeague Island, the largest Casco Bay island. In 2018, the high-high clusters are gone, and new low- high outliers around Great Chebeague Island and along Falmouth Foreside have taken their place (Figure 12). This picture changes in 2022, the most recent survey year as almost all high-high clusters and high-low outliers disappears (Figure 13) and are replaced by sporadic low-high outliers in the bay as well as low-low clusters off Portland, Falmouth, and Harpswell / Sebascodegan Island, where eelgrass acreage was previously notable.

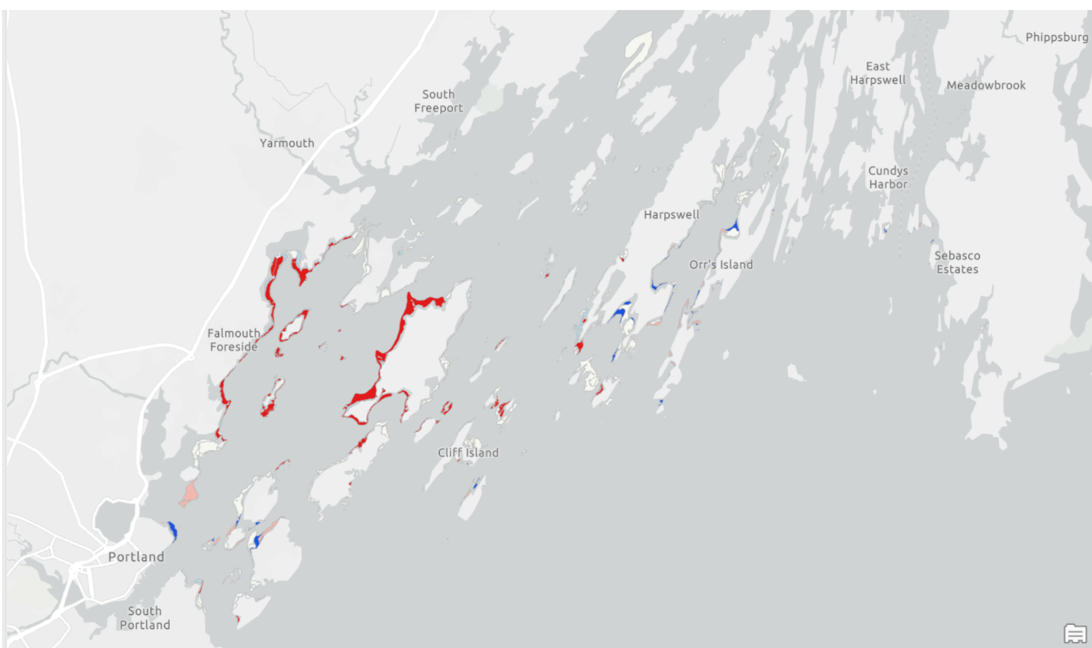

Figure 11: Local Moran's I of seagrass distribution, 2013. (Source: Author)

The disappearance of these high-high clusters suggests that areas previously characterized by strong, contiguous eelgrass populations are now experiencing a decline in density. The high-low outliers indicate regions where high eelgrass density is now surrounded by lower densities, pointing to a fragmentation or reduction in the overall health and extent of the eelgrass meadows, which could be caused by warming waters, invasive species, or non-point source pollution. Observing the transition from high-high clusters to high-low outliers highlights potential areas of concern where eelgrass populations are becoming less stable and more isolated, which could have implications for ecosystem health and resilience.

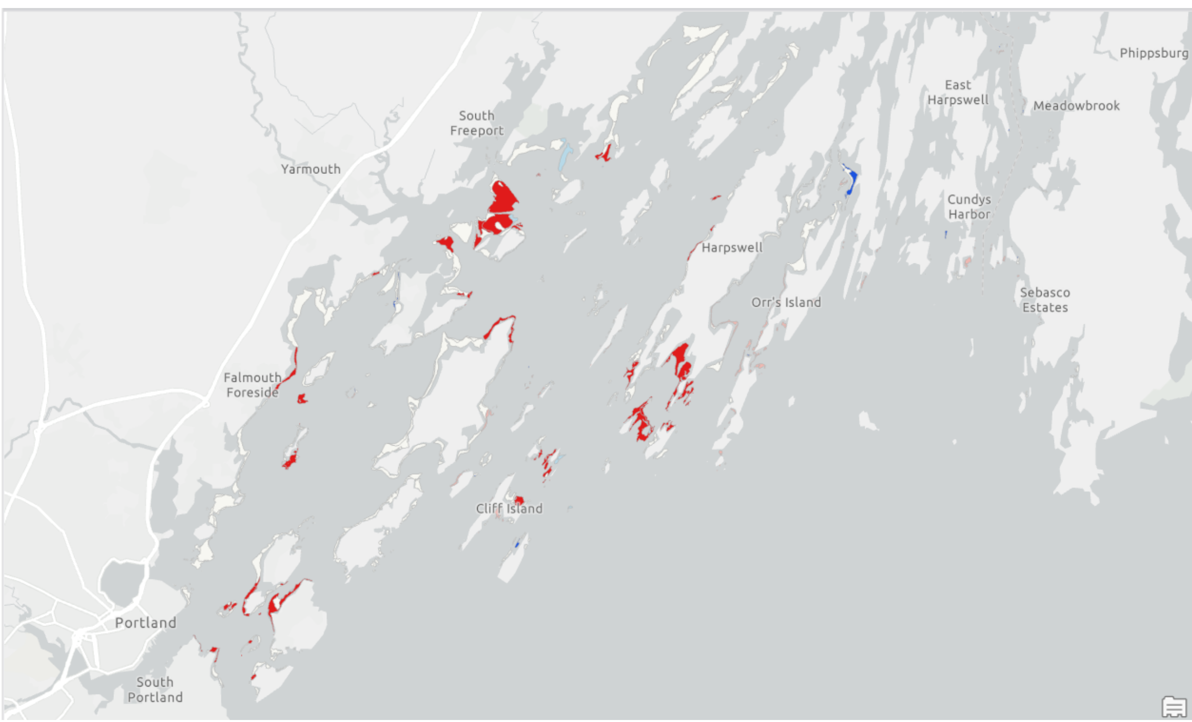

Figure 12: Local Moran's I of seagrass distribution, 2018. (Source: Author)

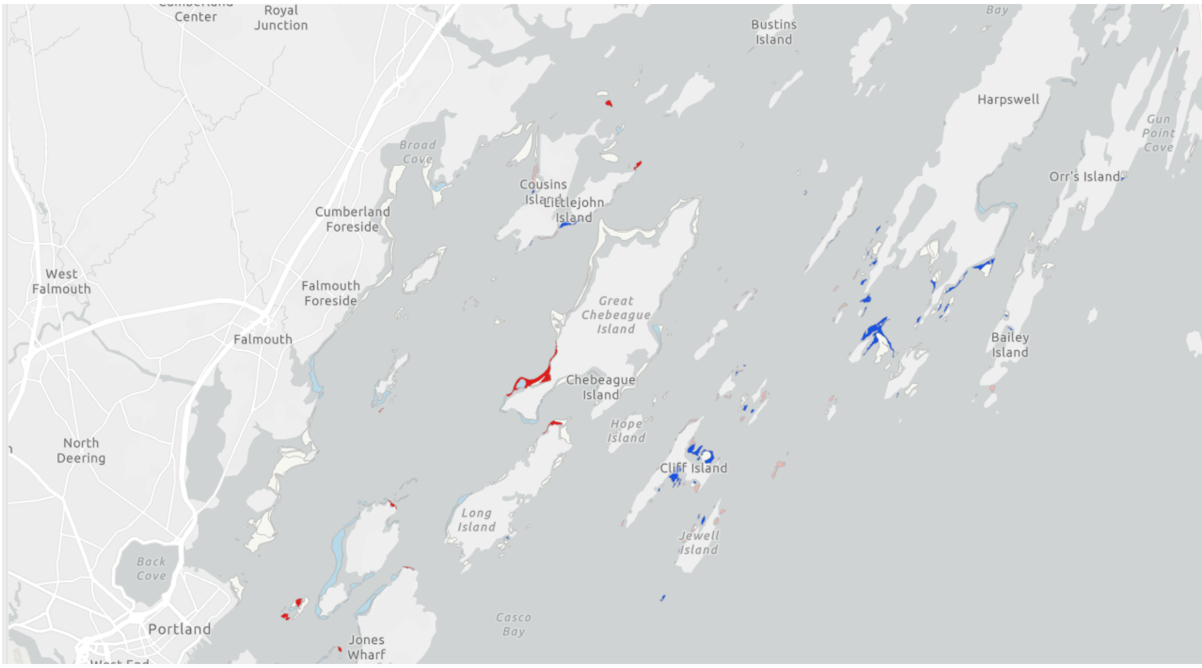

Figure 13: Local Moran's I of seagrass distribution, 2022. (Source: Author)

Moving onto the most recent set of 2022 data, there is little clustering to be seen at all. The few pockets that are observed are dark blue, meaning low-high clusters, or where eelgrass density is low compared to surrounding regions, again possibly due to environmental stressors. This is concerning because it points to an overall decline in population health. The lack of clustering, which is expected in healthy eelgrass meadows that expand as they grow, indicates there are no longer large patches to be found. The presence of primarily low-high clusters in the most recent study year suggests eelgrass meadows are becoming more fragmented over the years, with healthy beds shrinking, and remaining eelgrass becoming increasingly isolated. There may be continued environmental stressors contributing to their decline or localized factors not being properly mitigated.

Emerging Hotspot Analysis and Optimized Hotspot Analysis

To better understand these results, I chose to analyze them in conjunction with an Emerging Hotspot Analysis (EHSA) and Optimized Hotspot Analysis (OHA) to provide a more comprehensive understanding of the spatial patterns and dynamics of the eelgrass population. For instance, spatial patterns from Local Moran's I regarding clusters and outliers could be compared with the two hotspot analyses, which focuses on statistically significant hot and cold spots. Areas identified as high-high clusters in Local Moran's I should correspond to hot spots in the OHA, reinforcing the significance of these regions. Similarly, low-high clusters might align with cold spots or transitional zones in the OHA or EHSA.

This required a bit of data preprocessing to complete. While information on study years was technically available in the attribute table, they were in ArcGIS Text format and unable to be analyzed with a temporal Emerging Hotspot Analysis until this information was converted to the proper Date format. These steps were carried out for each eelgrass study layer by utilizing the Field Calculator and adding a new column that used the Python string function datetime.now() to obtain the correct year. For instance, *datetime.datetime.now() - datetime.timedelta(days=5.5*365)* was used for 2018 data because the seagrass meadows were studied by MaineDEP in Summer 2018, and *datetime.datetime.now() - datetime.timedelta(days=1.5*365)* was used for Summer 2022.

After this was done for all three layers, the datasets were combined using the Merge Feature tool. The newly merged data was used to generate a space-time cube for emerging hotspot analysis. An optimized hotspot analysis (OHA) was also conducted using the existing point data. 99% confidence is dark red, 95% confidence is dark orange, and 90% confidence is light orange.

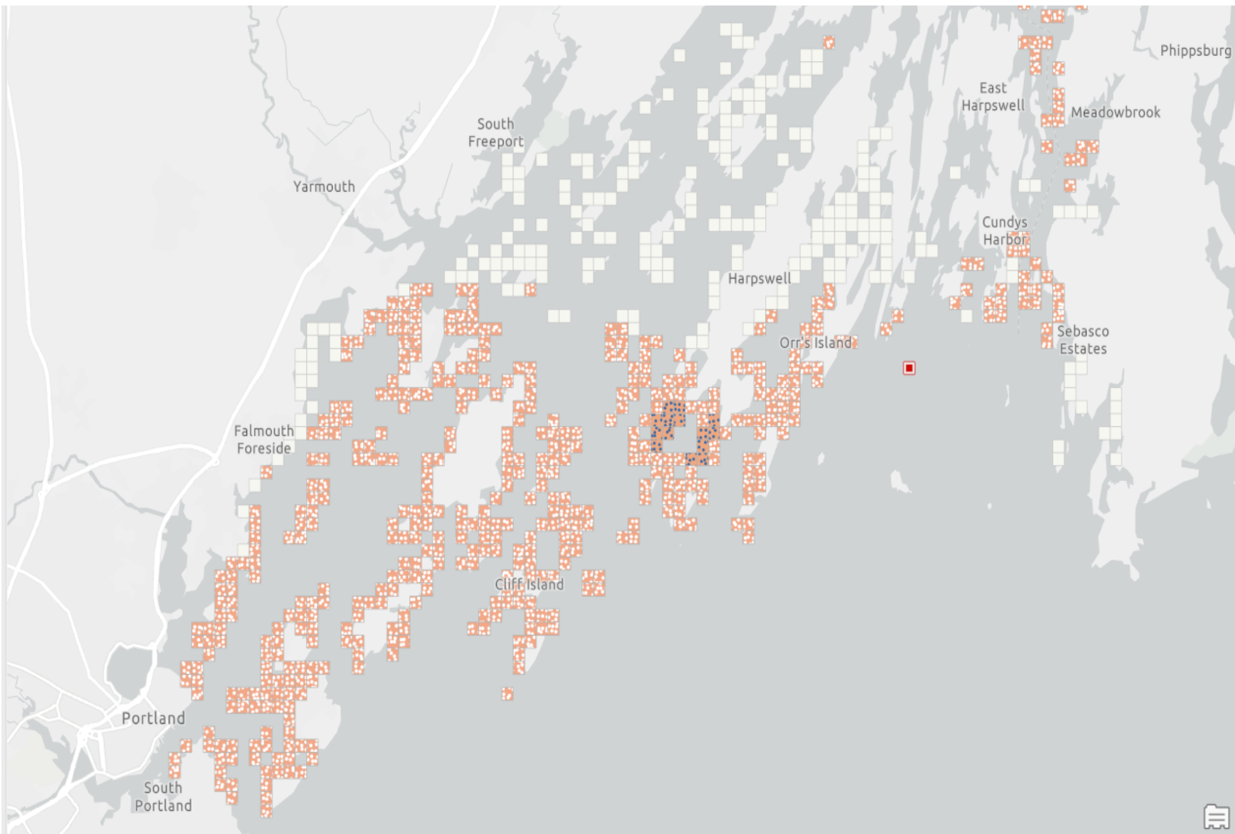

Figure 14: Emerging hotspot analysis for merged data. (Source: Author)

As seen in Figure 14 above, there were no persistent hotspots located, although most eelgrass locations in the southern half of the study area were identified as sporadic hotspots, with a pocket of oscillating hotspots south of Harpswell. Oscillating hotspots are areas where the intensity of a phenomenon fluctuates over time, alternating between being statistically significant hotspots and not being hotspots. This means that these regions have experienced periodic increases and decreases in eelgrass density over the study years.

Sporadic hotspots in the southern half suggest that high eelgrass density areas are not consistent over time but appear intermittently. This aligns with the idea of isolated, fragmented patches of eelgrass detected by the Local Moran's. The absence of a detectable pattern in the northern half of inner Casco Bay from the EHSA implies a lack of consistent spatial clustering over time, which corroborates the Local Moran's finding of no significant clustering in this region. Only one new EHSA hotspot was observed, east of Orr's Island. Both the Local Moran's and EHSA suggest fragmentation and inconsistency in eelgrass distribution – the former points to isolated patches of low density surrounded by higher density in the present day, while the EHSA's sporadic and oscillating hotspots also indicate temporal inconsistency in regional eelgrass presence.

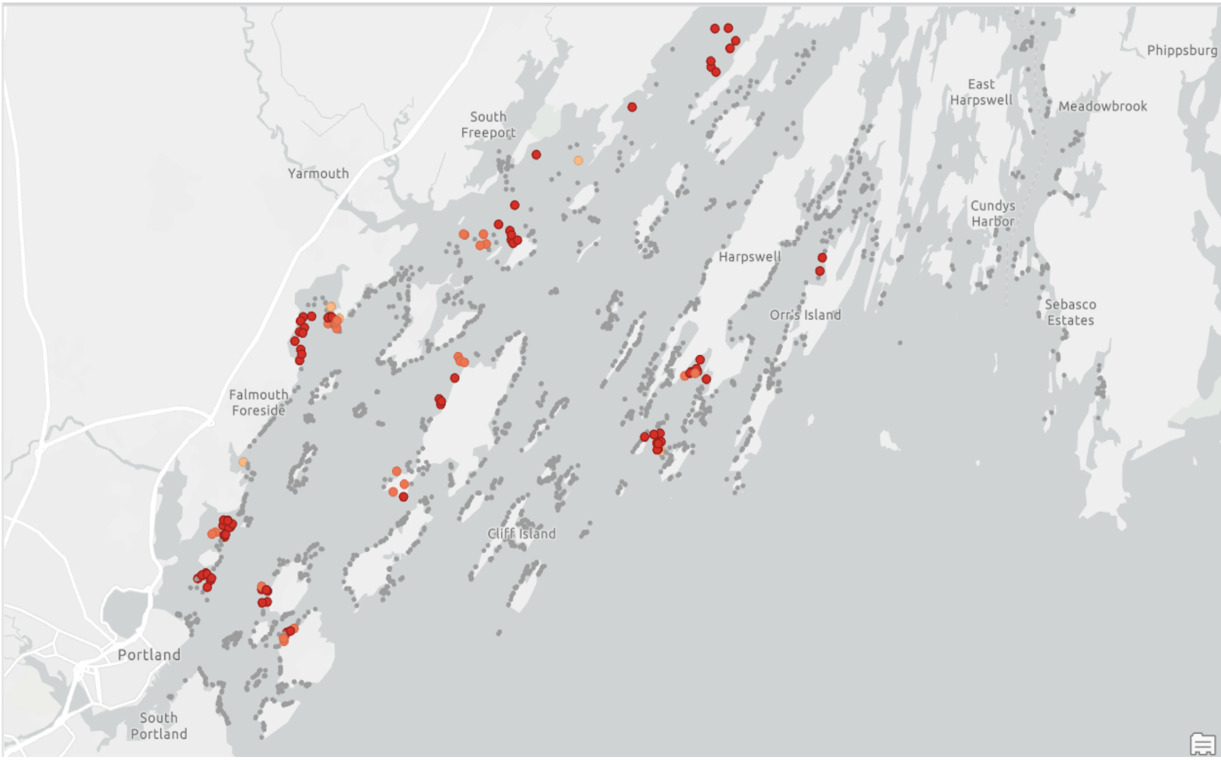

Figure 15: Optimized hotspot analysis for merged data. (Source: Author)

Regarding the Optimized Hotspot Analysis, when seagrass coverage was observed in full from 2013, 2018 and 2022, hotspots with 99% confidence in dark red were shown in the waters between Portland and Falmouth along with nearby Peaks Island (Figure 15). Furthermore, there were hotspots found in north Falmouth in Broad Cove and Moshier Island to the northeast. Moving further up the coast towards Freeport, there are even 99% hotspots in Maquoit Bay and Harpswell. Hotspots with 95% and 90% confidence are found close to all the hotspots, except for Maquoit Bay, which has been indicated as containing hotspots with the highest confidence overall. There are no cold spots from this analysis, although this could be due to the influence of earlier 2013 and 2018 data.

The 99% and 95% confidence hotspots from the OHA (Figure 15) provide a more definitive spatial delineation of the most critical areas for eelgrass. The presence of these high-confidence hotspots supports the Local Moran's I results by providing a broader spatial context and reinforcing the significance of identified clusters, including those of eelgrass meadows or beds that have been prominent in the past but not in the present-day.

MaxEnt Predictive Modeling

The core of this thesis revolved around using presence-only predictive modeling, and the MaxEnt model revealed intriguing insights about potential locations where seagrass could thrive. As expected, the darkest purple areas were around the small islands in Casco Bay, where ecological conditions support their growth. This was validated by their confirmed presence in the latest 2023 survey, such as off the coast of Portland, Maine and near Peaks Island. The map indicated that Harpswell and Sebascodegan Island were also likely locations for eelgrass to thrive.

With the Empirical Bayesian Kriging tool, five variables were interpolated to create five rasters. All the data from these variables – temperature, salinity, dissolved oxygen, turbidity, and total nitrogen – came from the Friends of Casco Bay monitoring stations (Figure 16). The FOCB data was originally in an Excel spreadsheet and the 19 monitoring stations utilized were manually geocoded in ArcGIS Pro using the XY Table to Point feature, as each monitoring station had longitude and latitude coordinates associated with it. In the software, the output cell size was set to

30 meters for higher granularity. Geocoding these points was the first step towards being able to conduct data interpolation throughout the Bay.

With the existing eelgrass point data and five interpolated layers, MaxEnt was run to predict the future location of eelgrass beds given recent environmental factors. The subsequent output was masked so that it would only focus on the Gulf of Maine region (Georges Bank, Figure A1), which was in the form of a vector shapefile from NOAA. Geospatial masking also had the benefit of taking significantly less time to run, as opposed to generating an output for the entire planet.

The MaxEnt tool was configured to be largely accessible, and I was able to follow an ESRI guide to understand how to utilize it. I used my merged eelgrass points data layer as the confirmed species presence input, and the interpolated EBK layers as the environmental covariates. From there, I set my output cell size again to 30 meters for consistency.

There was the option to include basis functions to transform the environmental data in order to better capture non-linear relationships, enhance model flexibility and improve performance of the model. Because of these benefits and the only tradeoff of a slightly longer run-time, I chose to use Linear, Squared, and Pairwise. The squared function listed was useful for helping the model fit parabolic trends, as seagrass does not respond to environmental covariates in a linear, or necessarily even predictable, fashion. Finally, I ensured that projected coordinates were set at UTM 19N for northern New England and masked appropriately to the Gulf of Maine.

A predictive raster (Figure 24) and response table (Figure 26) were generated for the model. I obtained additional model summary statistics from the MaxEnt tool (Figure A5).

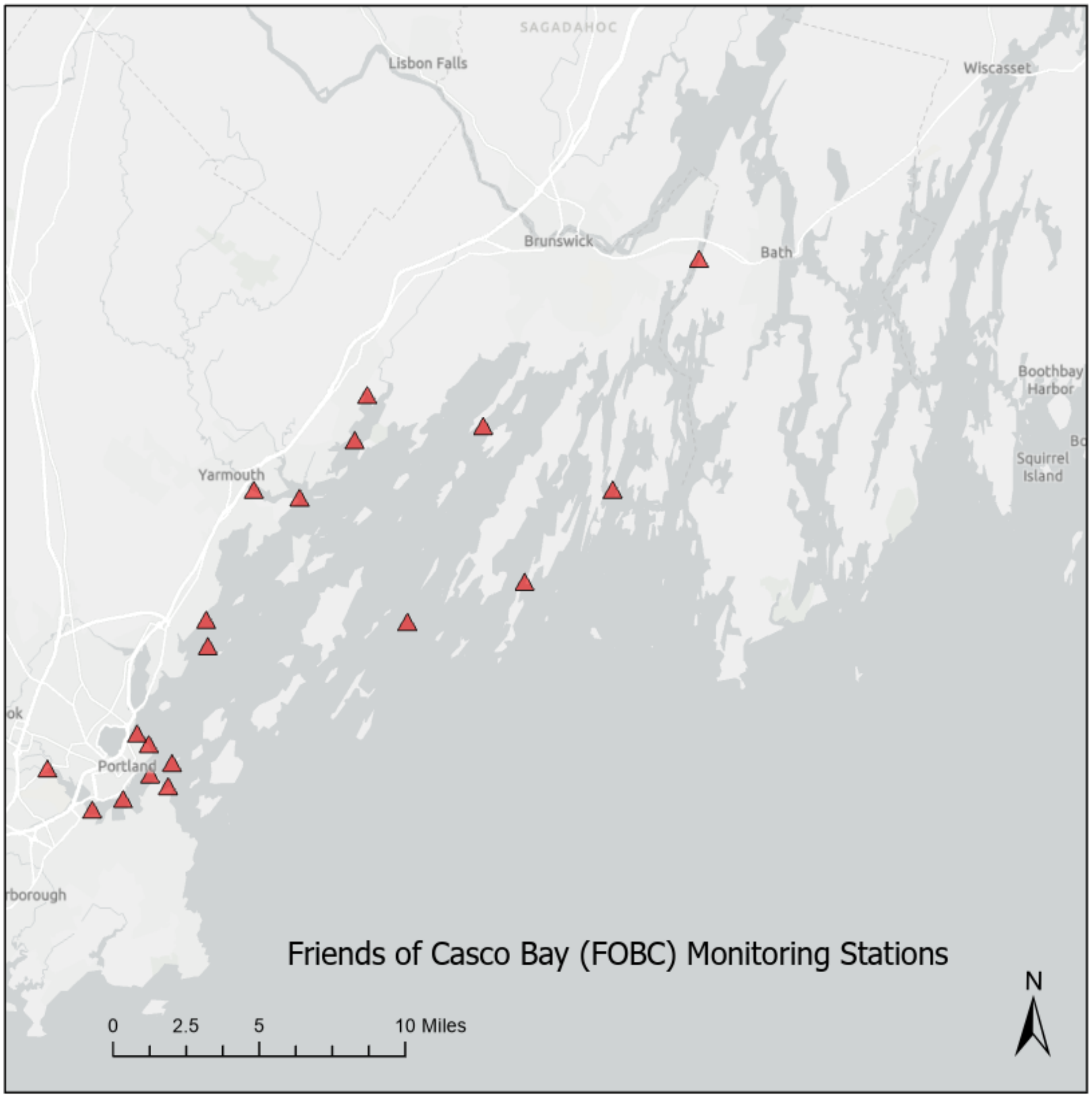

Figure 16: FOCB Monitoring Stations. (Source: Author)

Empirical Bayesian Kriging

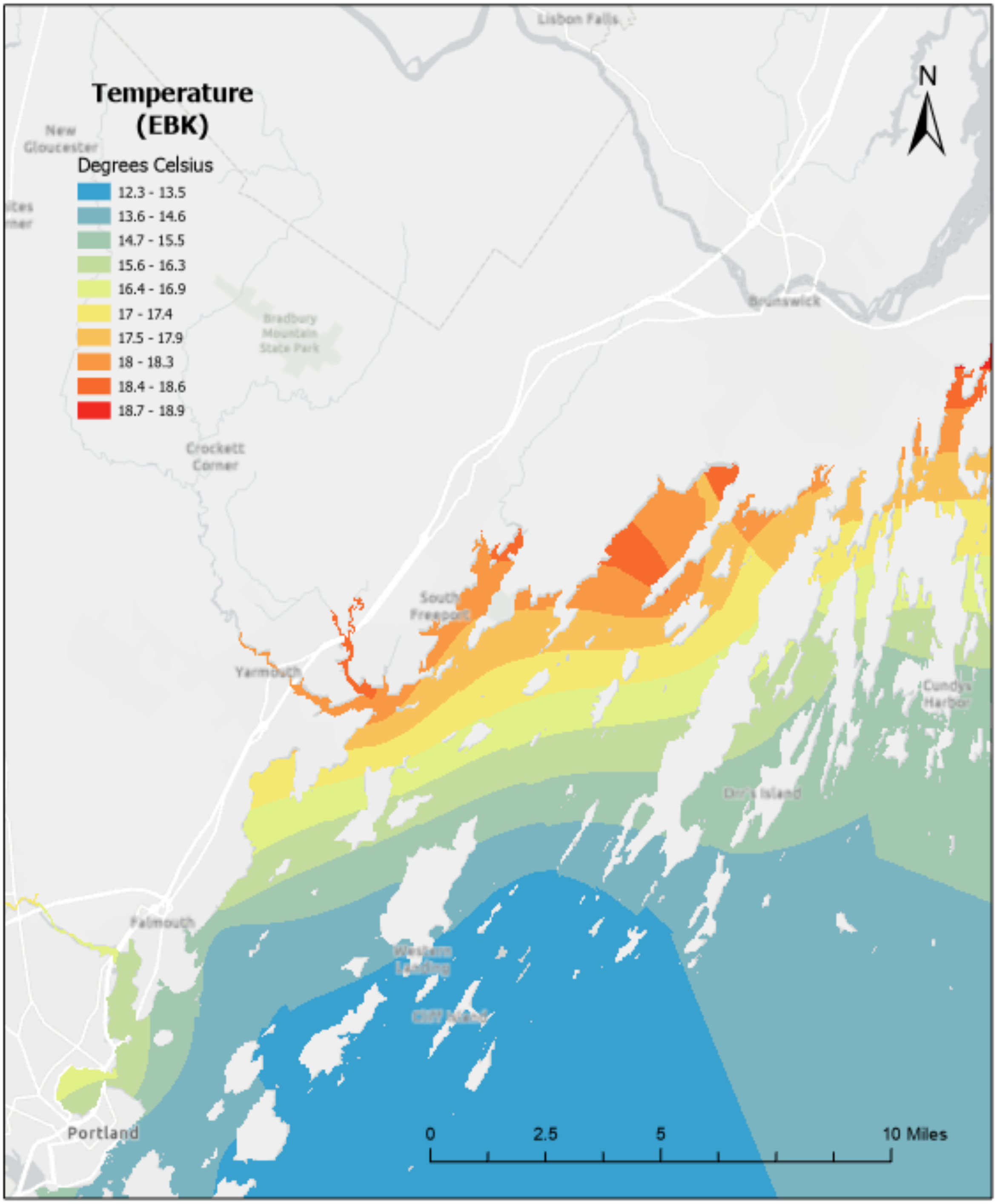

Figure 17: Temperature EBK (Source: Author)

Sea surface temperature (SST) in Casco Bay ranged from 16.4-16.9 degrees Celsius (61.5 to 62.4 degrees Fahrenheit) in the Back Cove neighborhood of Portland and between 14.7 to 16.3 degrees C (58.5 to 61.3 F) in the nearshore waters (Figure 17). SST increased further north, with interpolated temperatures as high as 18.7 to 18.9 degrees Celsius (65.6 to 66 degrees Fahrenheit) in the inlets near Yarmouth, South Freeport, and Brunswick. Excessively warm waters pose hazards to eelgrass because they do not grow as well under high water temperatures. Furthermore, the invasive green crab, which appears to be one of *Zostera marina's* greatest threats because of its tendency to uproot and clip seagrass in its search for food and shelter, prefers warmer oceans (Howard, 2019).

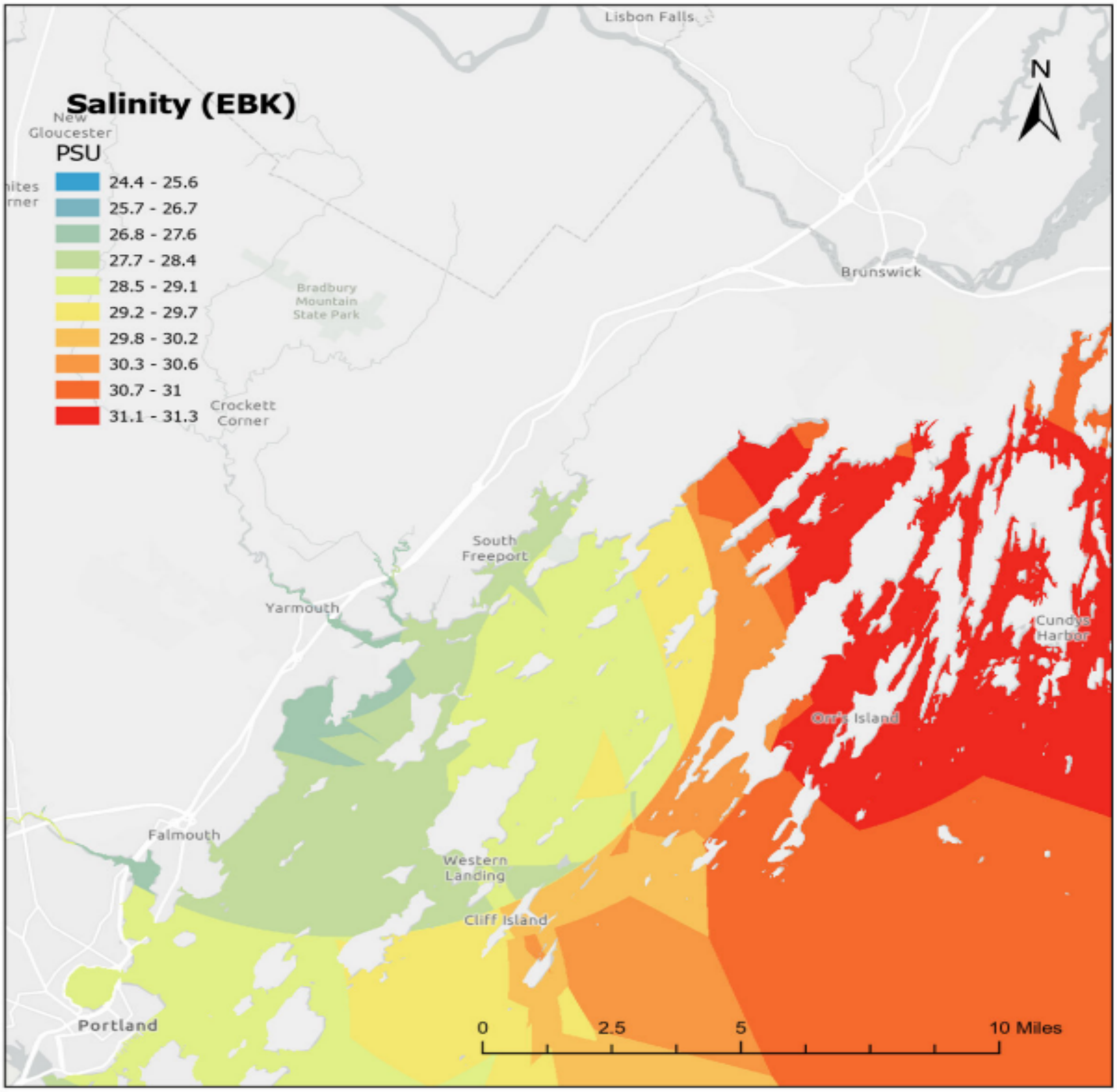

Figure 18: Salinity EBK (Source: Author)

Salinity from FOCB was defined in Practical Salinity Units (PSU), which is where a gram of salt per 1000 grams of water represents one PSU (Reid, 2006). Per the Cornell Cooperative Extension, *Zostera marina* prefers estuarine or polyhaline waters where salinities range from 20 to 31 ppt. If salinities drop below that level, eelgrass meadows can survive, but productive capacity is reduced by up to 50% (CCE, 2012). It appears that salinity ranged from 25.7 PSU near the

Yarmouth coast to 31.3 PSU in northeastern Casco Bay, but all these numbers fell within the acceptable range (Figure 18).

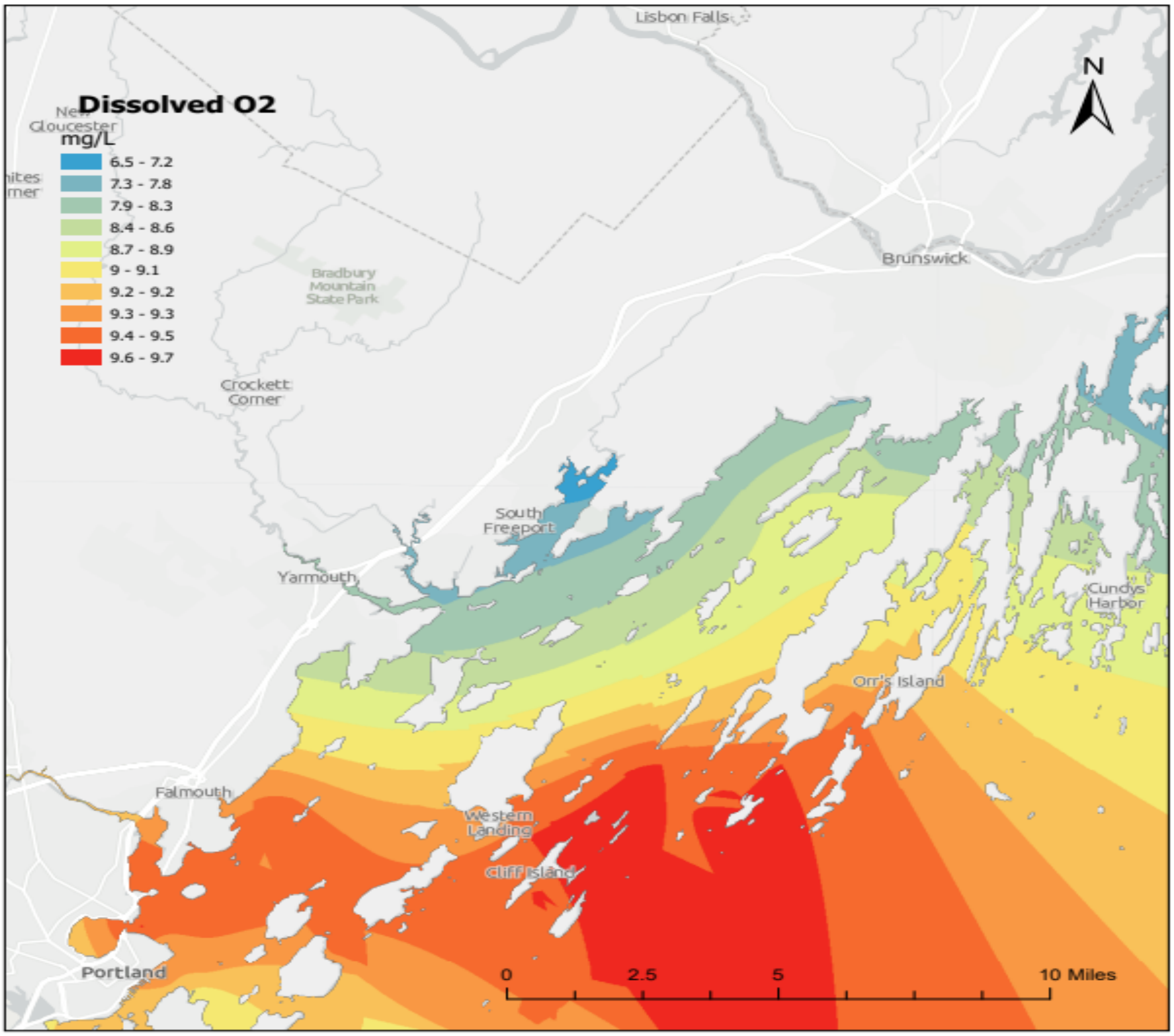

Figure 19: Dissolved O2 EBK (Source: Author)

Dissolved oxygen ranged from 6.5 to 7.2 mg/L near South Freeport and gradually increased in concentration from there (Figure 19). Moving in this striated pattern, the highest concentrations of dissolved O2 were found east of Cliff Island. Low levels of dissolved oxygen, such as less than <4 mg/L, were shown to be detrimental to eelgrass survival (Moore and Jarvis, 2008). Dissolved oxygen levels are expected to be lower near the shoreline due to increased nutrient loading, water exchange, and algal blooms, whereas higher water circulation moving into the bay stabilizes the level of DO2.

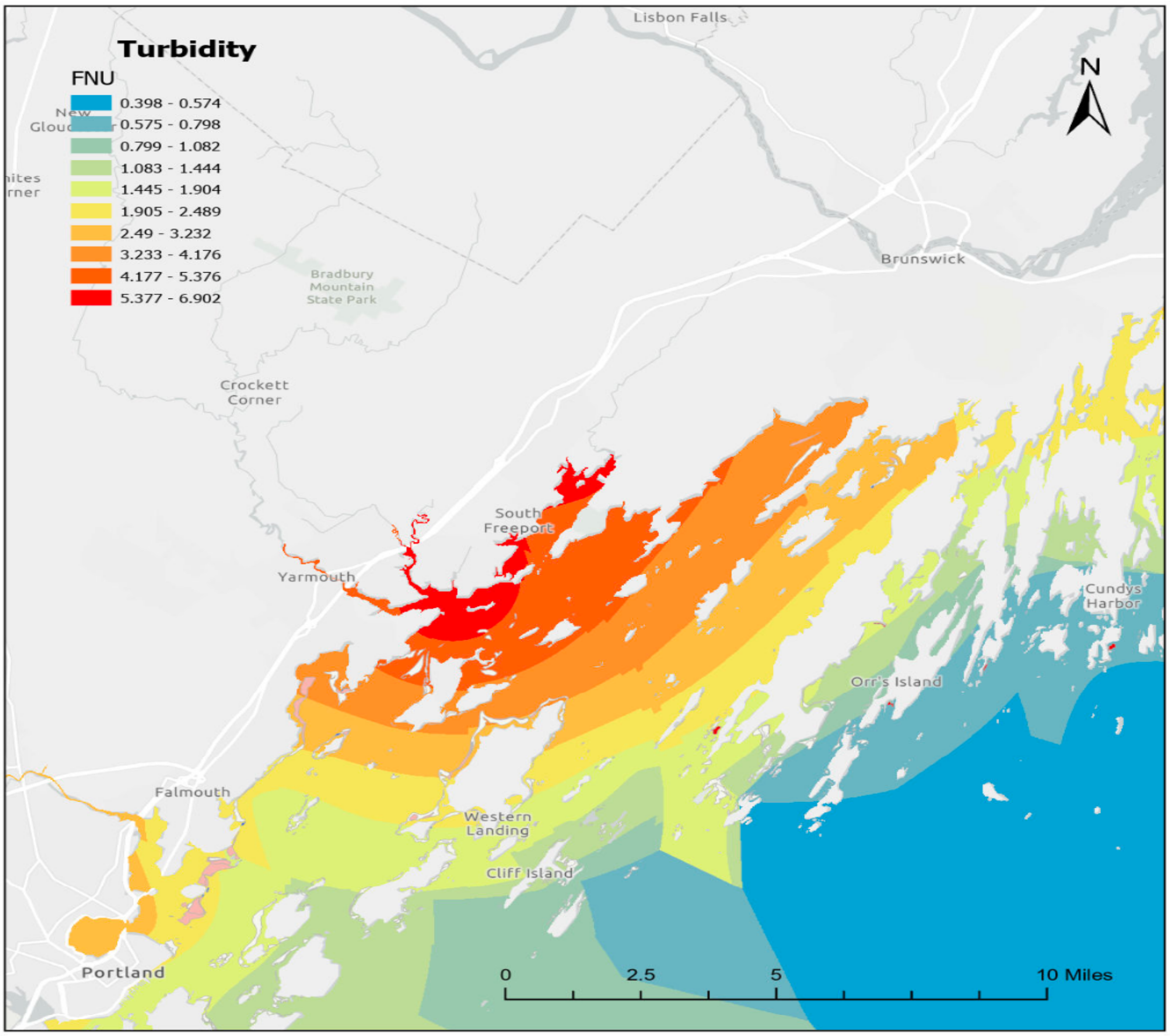

Figure 20: Turbidity EBK (Source: Author)

Turbidity was measured in Formazin Nephelometric Units (FNU), a unit measuring infrared light scattered through the water at a 90-degree angle (USGS, n.d.). The higher the FNU, the cloudier the water is. Turbidity was the highest in coastal Yarmouth and South Freeport and gradually became clearer in bands moving southwest (Figure 20). Higher FNU is expected near the coastline because of wave action, sedimentary runoff, and human activities like boating, whereas dilution of suspended particulates occurs the further one gets away from the coastline.

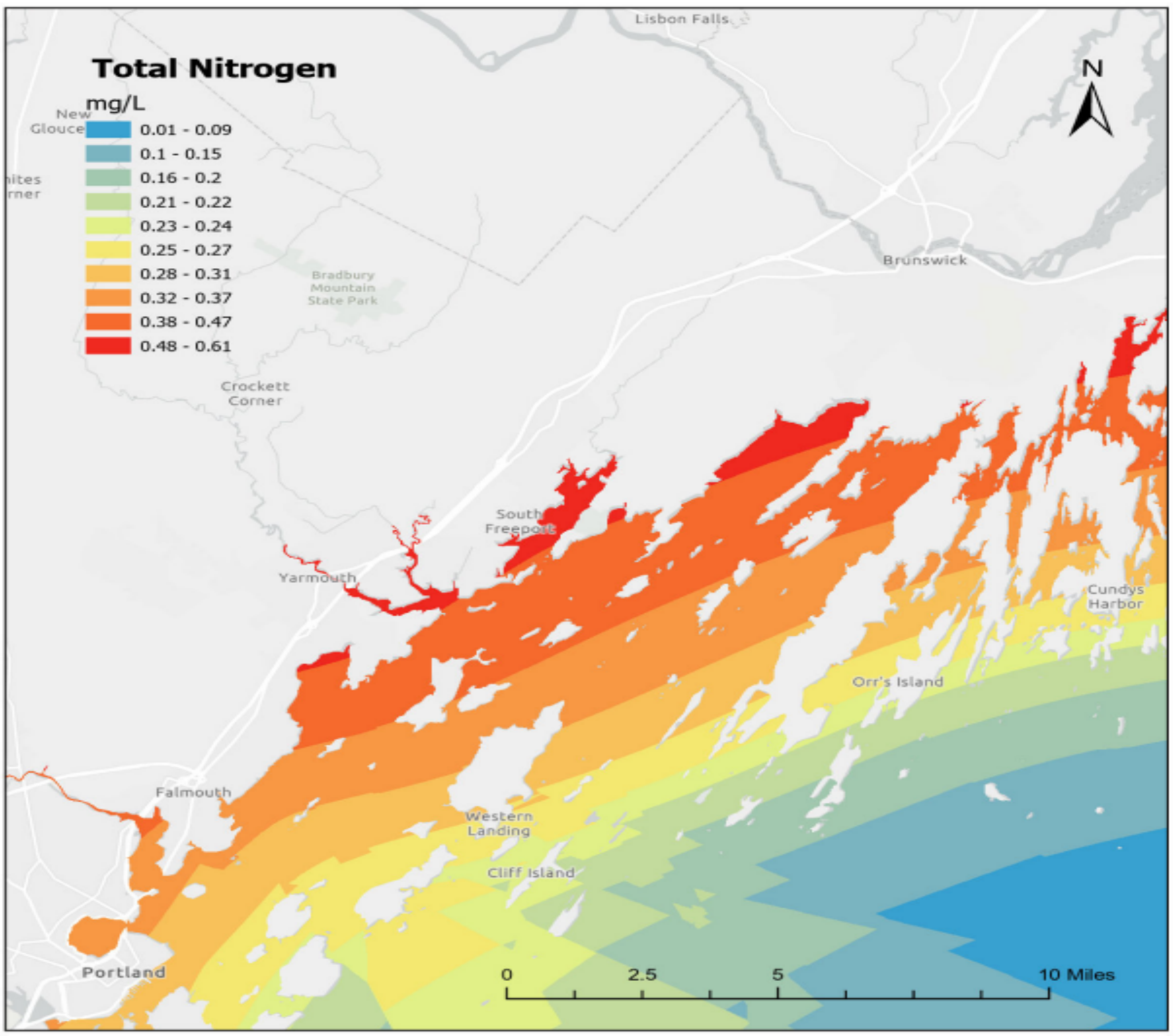

Figure 21: Total Nitrogen EBK (Source: Author)

Like turbidity, total nitrogen (TN) was found in higher concentrations along the coastline and gradually dissipated towards the open ocean (Figure 21). Levels up to 0.61 mg/L were observed near Yarmouth and South Freeport, while the Portland nearshore zone had TN levels ranging from 0.32 mg/L to 0.37 mg/L. Higher total nitrogen concentrations near the coast are usually due to inputs from riverine discharge, urban runoff, agricultural runoff, wastewater discharge. Because eelgrass requires nitrogen for growth and photosynthesis, their presence in higher concentrations is beneficial for the environment. However, there is a delicate balance to be struck, as excessively elevated levels of TN can lead to eutrophication and the promotion of harmful algal blooms.

Topo to Raster

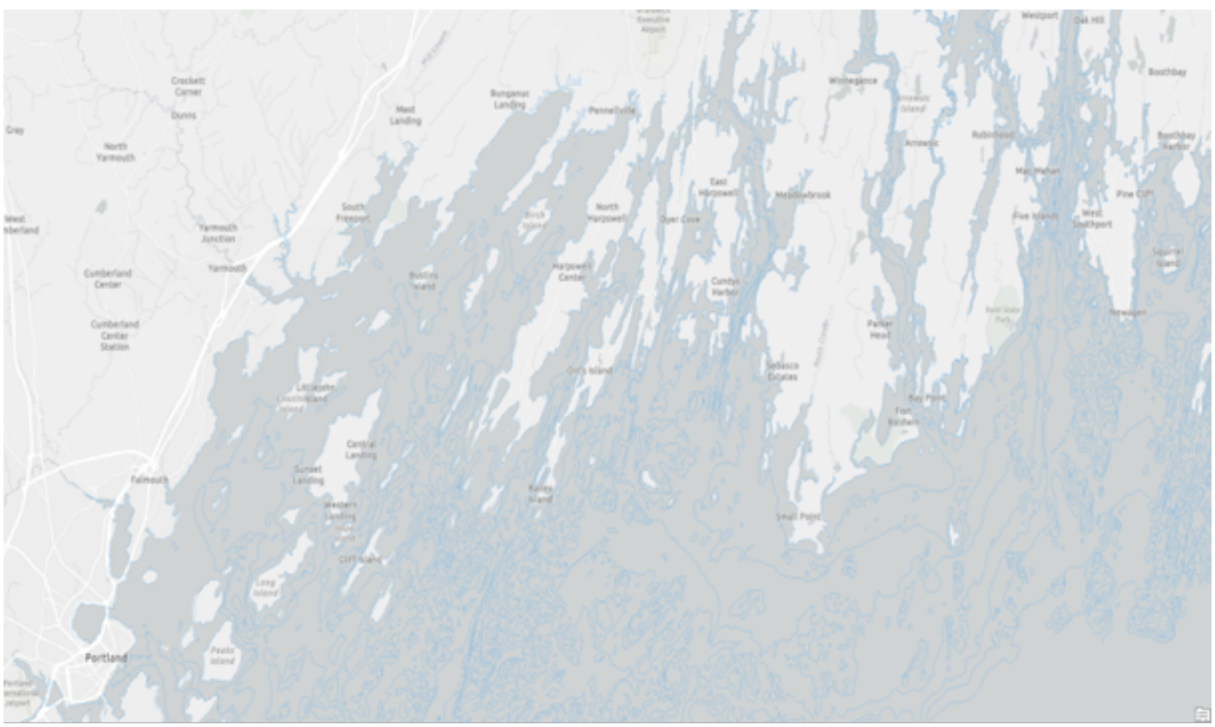

Figure 22: 1:100,000 Contour Lines for the Gulf of Maine (State of Maine)

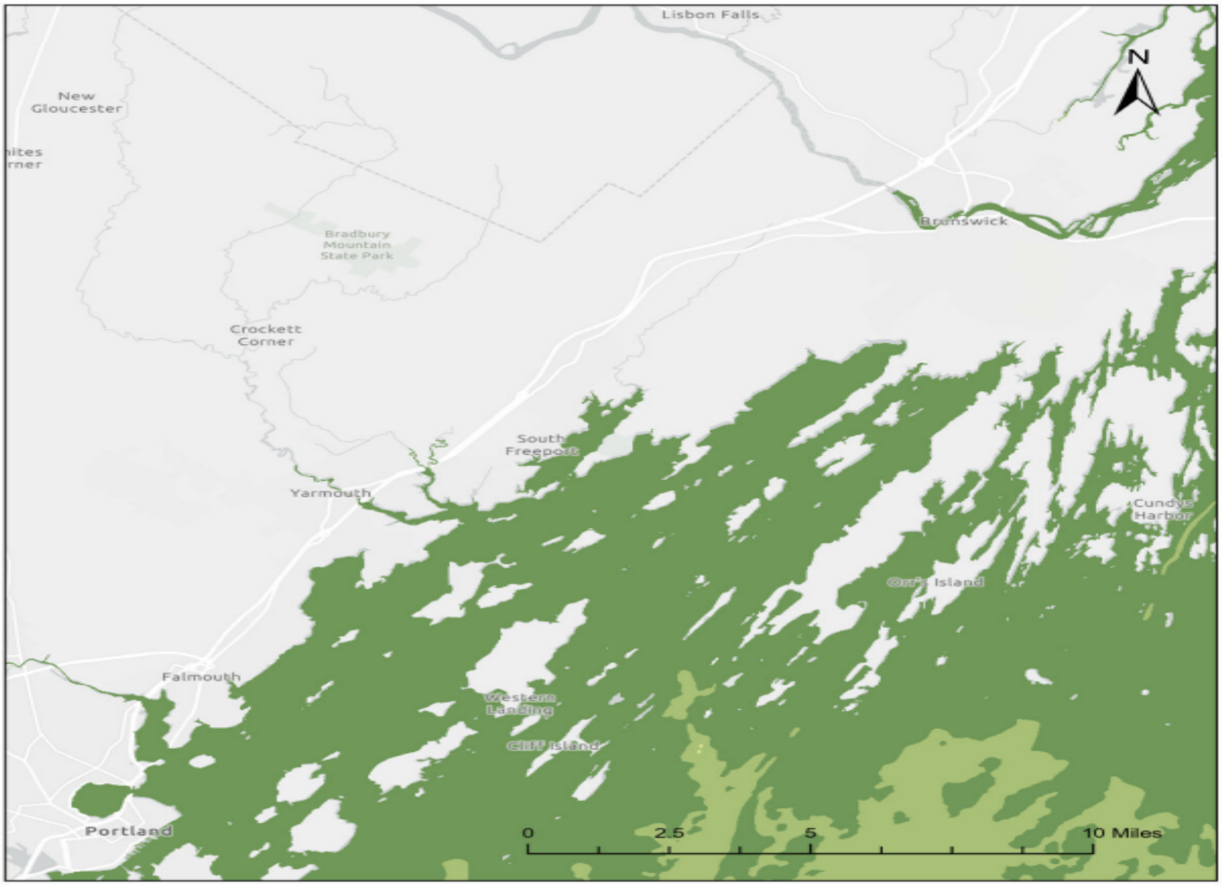

Figure 23: Bathymetric Depth of Casco Bay (Source: Author)

Bathymetry, which refers to the underwater topography or depth of the seabed, plays a crucial role in eelgrass growth and development. The 1:100,000 contour lines (Figure 22) were converted into a raster format using the Topo to Raster feature in ArcGIS Pro, resulting in the map above (Figure 23). This data conversion permitted the layer to be analyzed alongside the other five covariates in the MaxEnt model.

MaxEnt Results

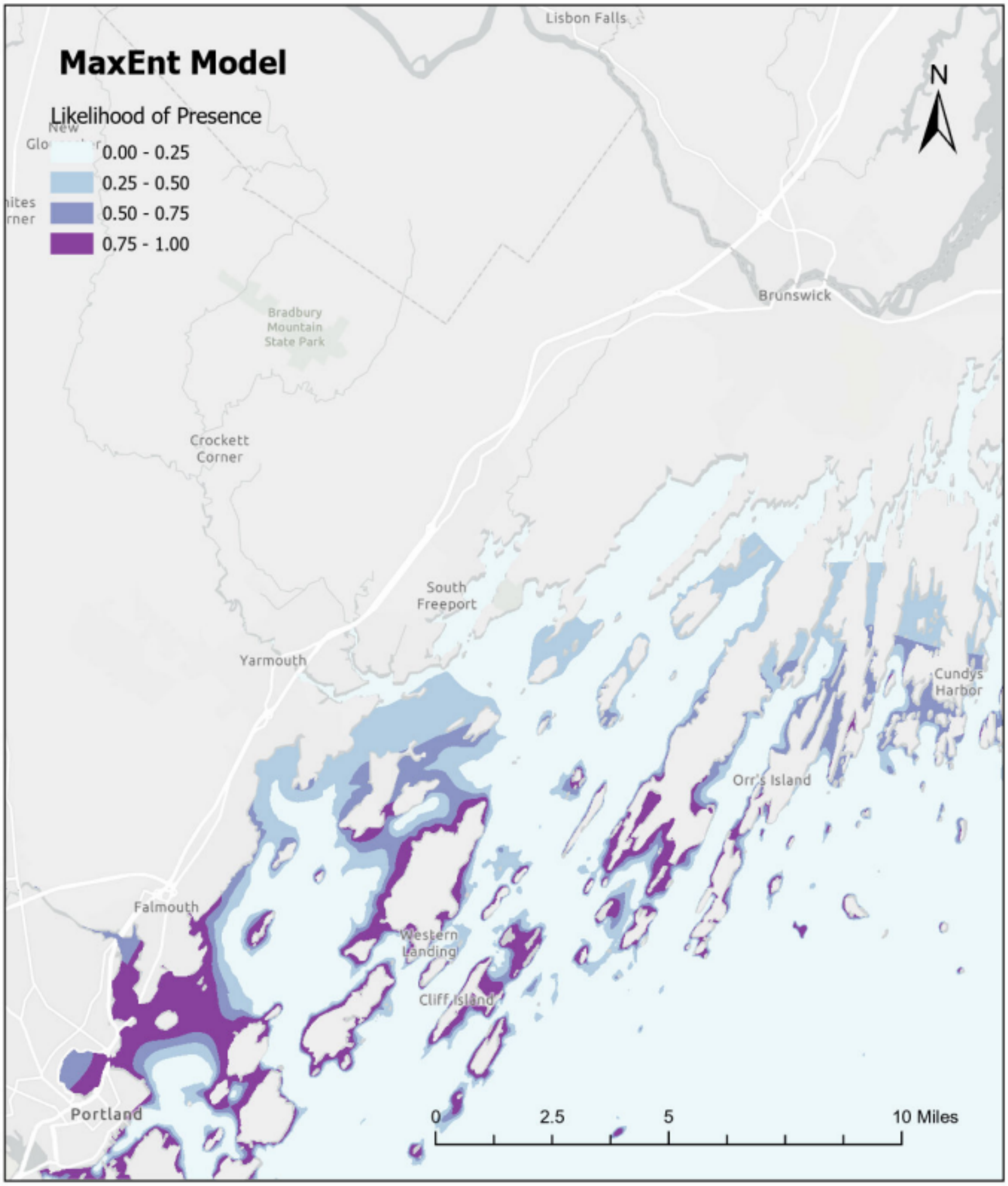

Figure 24: MaxEnt Results for Eelgrass (Source: Author)

As mentioned previously, this MaxEnt model (Figure 24) represents the likelihood of eelgrass presence in Casco Bay, which can be used for ecological conservation and policymaking purposes. Starting from the lower left corner of the map, near Portland, it appears the highest likelihood of presence is northeast of the city – between Portland and Falmouth – and includes the small, circular island called Mackworth Island. This would be a region that should be of highest priority to eelgrass conservationists, not only because of the high likelihood of eelgrass presence and habitat suitability, but also because of its proximity to the major economic engine of Portland, which can offer resources for outreach and protection. If this model is accurate, this continuous swathe would be very promising to protect. To the east, the coastlines of the three closest Casco Bay islands to the mainland are also indicated as very high likelihood for eelgrass, at 75 to 100%. Great Diamond Island is surrounded in a purple ring, and so is most of Peaks Island. Cushing Island also has a narrow band of purple around its northern end.

Moving onto the deeper islands in the Bay, the islands near the Western Landing (Great Chebeague Island) and Cliff Island similarly experience the highest levels of eelgrass presence and are surrounded by dark purple. The trio of small islands in the form of Stave Island, Ministerial Island, and Bates Island (Figure 25) were also surrounded by dark purple, indicating promising eelgrass presence. This all aligns with the notion that nearshore and intertidal zones are considered highly suitable for eelgrass, and the gentle topography of coastal bathymetry in this region would also benefit eelgrass in terms of habitat and sufficient light for photosynthesis. Slightly northwest of these two islands is a zone that is demarcated as light blue and blue purple for likelihoods of presence of 25 to 50%, and 50 to 75%, respectively. This region stretches from Cousins Island back towards the mainland, southeast of Yarmouth.

Figure 25: Trio of islands with high likelihood of eelgrass. (Source: Author, Google Maps)

Finally, moving towards the scattered islands and long peninsulas of northeastern Casco Bay, such as in Harpswell, Orr's Island, and Sebascodegan Island – sweeping from left to right – it appears the last noticeable pocket of high eelgrass presence is on the coastline of the three-pronged peninsula of Harpswell. The sheltered coves and lower development in this part of coastal Maine may contribute to this zone being productive for eelgrass presence. Traveling northeastward from this geographic area, Cundy's Harbor appears to be rather appealing for eelgrass as it is ringed by blue purple, indicating the MaxEnt model believes the likelihood of its presence in this area is 50 to 75%. This amount is probably high enough to warrant a closer look by environmental deputies and conservation agents, particularly as the working waterfronts would receive strong co-benefits from a robust blue economy, in part brought about by the continued thriving of eelgrass here.

MaxEnt Tables and Plots

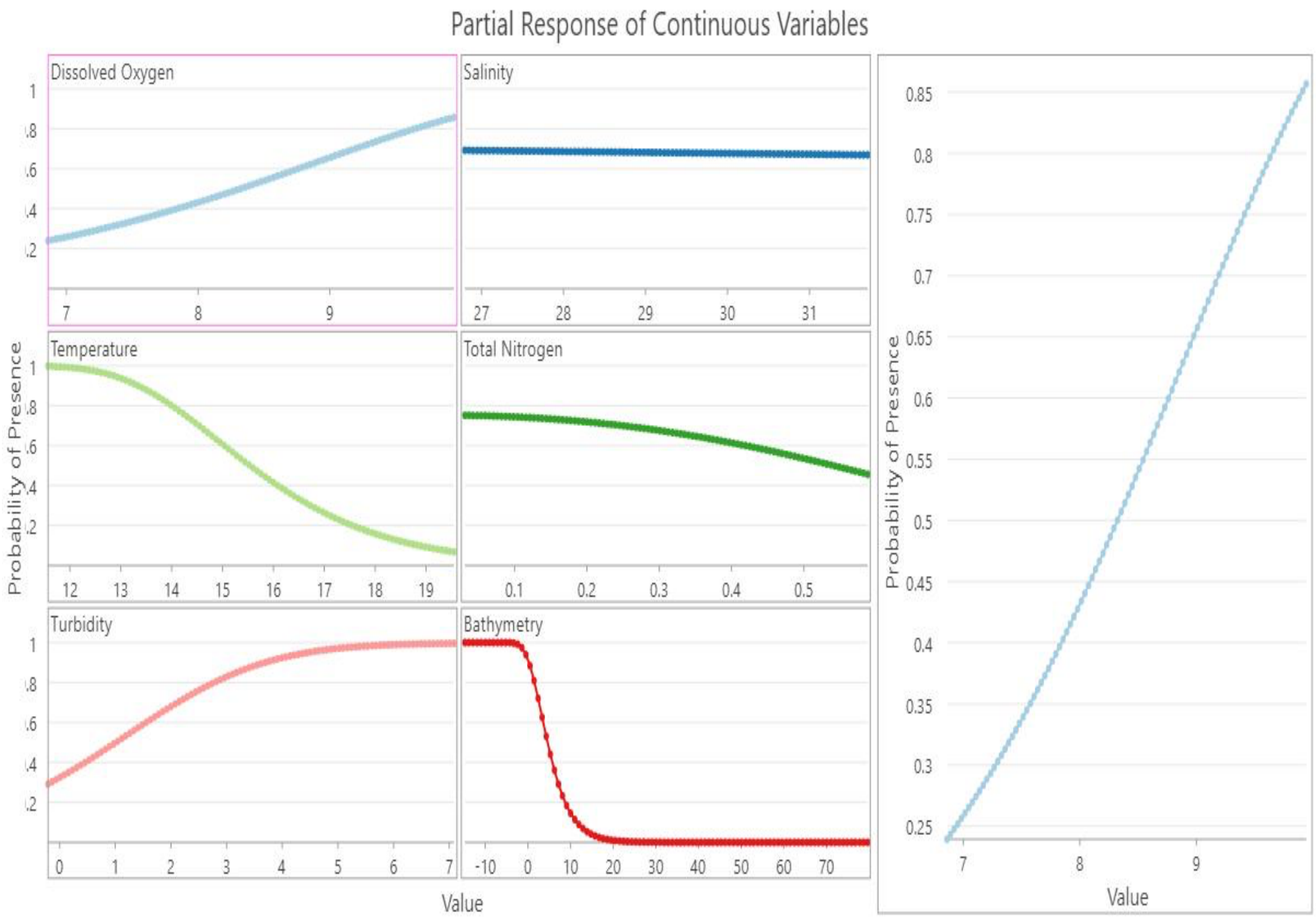

Figure 26: Partial Response of Continuous Variables

As temperature increases, the probability of eelgrass presence decreases, indicating a downward logistic trend. Eelgrass might prefer cooler water temperatures, and higher temperatures may be beyond its optimal range, leading to stress and reduced growth. Beyond said range, metabolic stress, reduced growth rates, and increased susceptibility to disease can occur, as seen by Nejrup and Pedersen (2006). Out of the six variables analyzed, temperature appeared to have the largest impact on eelgrass presence and presumptive survival, based on these charts.

The flat response curve indicates that salinity does not significantly affect the probability of eelgrass presence within the range of salinity values in the region. This makes sense as the salinity range did not vary significantly throughout the study area. Eelgrass might be tolerant to a wide range of salinity levels, or the variation in salinity within my study area might be too narrow to show a strong effect. In addition, eelgrass can often be found in both estuarine and coastal marine environments, which typically have varying salinity levels. The flat response implies that within the observed range, salinity is not a limiting factor for eelgrass growth and distribution, allowing other environmental variables to play a more defining role, at least in the context of Casco Bay.

As dissolved oxygen levels increase, the probability of eelgrass presence slightly increases. The positive slope for the logistic curve for dissolved oxygen (DO2) suggests that higher oxygen levels increase the suitability for eelgrass presence. After all, dissolved oxygen is crucial for the respiration of eelgrass and associated marine organisms. Higher dissolved oxygen levels are generally beneficial for eelgrass, supporting better respiration and overall health. On the other hand, oxygen levels that are too low can lead to hypoxic conditions, threatening the meadows. This trend underscores the importance of maintaining good water quality with adequate levels of oxygenation.

As turbidity increases, the probability of eelgrass presence increases. This is somewhat counterintuitive as high turbidity usually reduces light availability. However, this might indicate that eelgrass in the Casco Bay area is adapted to turbid conditions, possibly because of reduced competition from other species or less predation. Turbidity in and of itself may be too "murky" of a factor alone, and light attenuation may have been a good option to analyze alongside it. Taken at face value, high turbidity could indicate areas with less competition from other light-demanding species or reduced grazing pressure from herbivores that prefer clearer waters.

The probability of eelgrass presence initially decreases as total nitrogen levels increase, suggesting that moderate amounts of total nitrogen might be beneficial, but higher levels may lead to eutrophication, which can negatively impact eelgrass by promoting algal blooms and reducing light availability. The curve suggests that while some nitrogen is beneficial, high concentrations are detrimental, serving as a reminder that adequate total nitrogen management is important to maintain balanced nutrient levels.

Finally, the probability of eelgrass presence sharply decreases with increasing depth. This was expected as eelgrass requires sufficient light for photosynthesis, which diminishes as the water becomes deeper. The sharp drop indicates a depth threshold beyond which eelgrass cannot survive due to insufficient light. Shallower, well-lit environments without the presence of competing species or nutrient oversaturation are generally considered ideal for eelgrass growth conditions.

Analyzing each environmental variable or covariate was important for understanding this model (Figure 26). Each one, even the comparatively flat salinity, plays a distinct role in shaping the suitability of habitats for eelgrass. Temperature and depth are significant limiting factors, with eelgrass showing clear preferences for cooler, shallower waters. Dissolved oxygen and moderate nitrogen levels support eelgrass health, while excessive nitrogen and high temperatures pose risks to be addressed in environmental management plans.

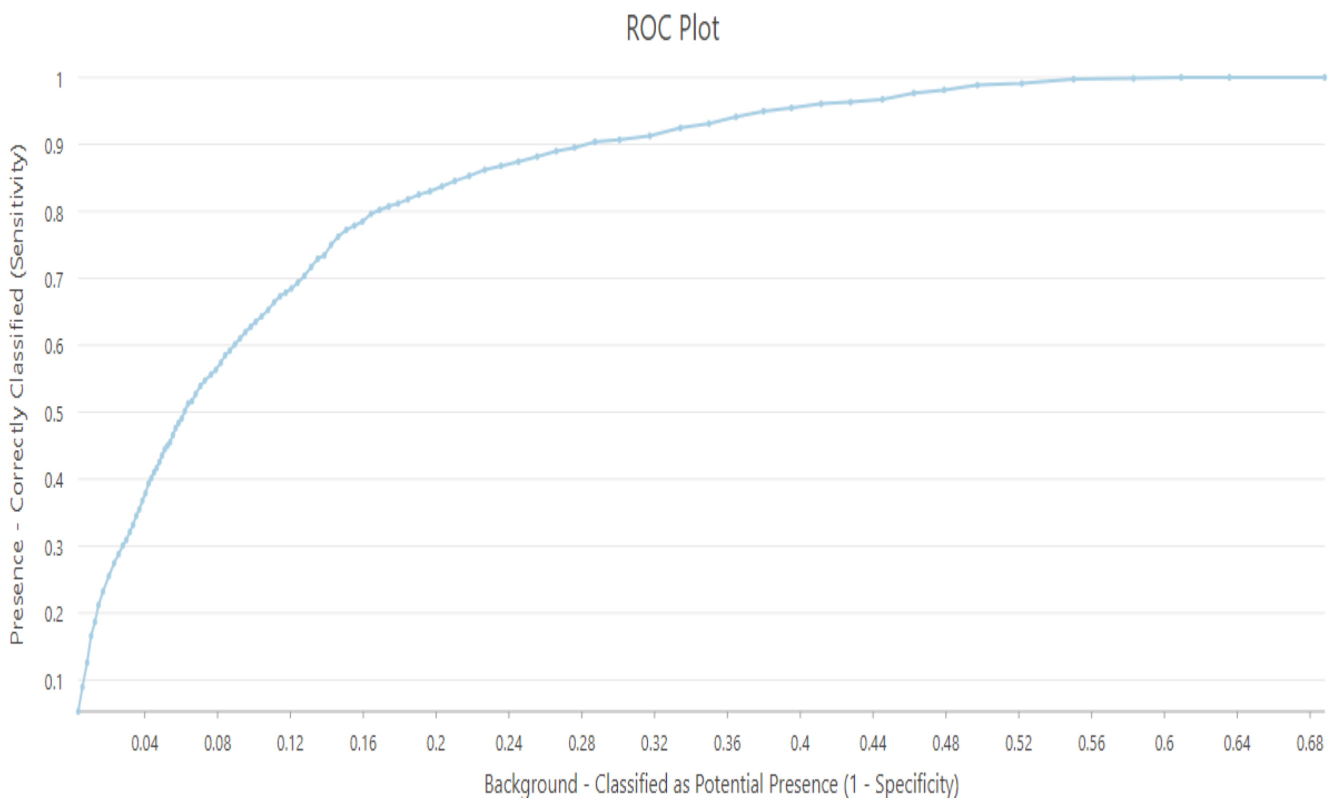

Figure 27: ROC Plot (Source: Author)

In Figure 27, the X- axis represents the proportion of true positive predictions, ranging from 0 to 1. It indicates how well the model correctly classifies actual presence points of eelgrass, with a value closer to 1 meaning accurate. The Y-axis represents the proportion of background points (e.g., areas where eelgrass is not present) that are incorrectly classified as potential presence. The range provided indicates the false positive rate, with higher values meaning more background points are misclassified as presence.

This concave downward yet increasing ROC curve indicates the model has good predictive ability. At lower thresholds where the curve is steeper, the presence of eelgrass is accurately predicted by the model, showing its efficacy at identifying areas where eelgrass is likely found, as seen in Figure 24. False positives — as the threshold increases, the model starts to misclassify more background points as potential eelgrass presence, and following the curve as it flattens, true positive rates come at the cost of higher false positive rates.

Using the ROC plot to assess the overall performance of the MaxEnt model helped me understand its performance and how it reliably distinguished between presence and absence of study points.

AUC	0.8915
Omission Rate	0.3402

Table 2: MaxEnt Model Summary

Table 2 above describes the MaxEnt model summary for AUC and Omission Rates. AUC values close to 1 indicates excellent model performance, while a value closer to 0.5 suggests a model without discriminative ability, which could arise from guessing randomly. An AUC of 0.892 is considered high, indicating that the model has excellent predictive accuracy. The other factor, the omission rate, is the proportion of true presence points that the model fails to predict. The stated omission rate of 0.34 means that 34% of the actual presence points were not predicted by the model

(Figure A4). While this demonstrates that a significant portion of presence points were missed, the high AUC suggests that the model is still generally reliable.

Interpreting these two points highlights where the model could be fine-tuned to reduce the number of false negatives. For future studies, I can aim to understand how specific environmental conditions were not adequately captured by the current set of covariates, such as turbidity, leading to lower accuracy. By addressing these factors, I can further enhance the MaxEnt model's utility for eelgrass conservation and management in Casco Bay.

Chapter 5: Discussion, Policy Implications, and Future Work

This predictive eelgrass model is intended to be an exploratory effort and does not fully encompass the range of factors influencing their ecological health (Figure 27). With that in mind, there are several key policy implications that the State of Maine, local municipalities, or environmental research groups in the region can note.

One of the most important ones is to enact legislation that will permit eelgrass to be at the forefront of conservation efforts and allow them to exist in tandem with other economic drivers of the Maine economy, such as fisheries and tourism. *State Law L.D. 593*, "An Act to Restore Regular Eelgrass Mapping in the State", was enacted in October 2021 through the efforts of State Representative Joyce McCreight and supported by the Friends of Casco Bay and the Nature Conservancy (Oliver, 2021). Through this act, each section of coastal Maine will be regularly mapped in five-year intervals to provide routine information about the status and health of eelgrass meadows and salt marshes, both crucial carbon sinks (State of Maine Legislature, 2021). Geospatial elements will be handled by the Maine Department of Environmental Protection and published on the Maine GeoLibrary site, a useful resource where I was able to get my footing on the GIS repositories available for the state.

Sufficient funding should also be allocated on the state and regional level to important nonprofits and agencies, such as the Friends of Casco Bay, Casco Bay Estuary Partnership, and the Maine Department of Environmental Protection. Existing initiatives from these groups provide extremely valuable data, and I would not have been able to carry out this research without the type of environmental information they made available for access or upon request. Their efforts should be widely supported to allow these scientists to keep on conducting their work.

Additionally, conservation efforts should be targeted towards areas that were identified as high likelihood for eelgrass meadow presence, such as between Portland and Falmouth (particularly Mackworth Island) and the notable islands of Greater Chebeague, Long Island, Great Diamond Island, and Peaks Island. In the northeastern part of Casco Bay, by Maine's Midcoast, the Harpswell Peninsula and Orr's Island also contained significant eelgrass presence, revealing another region worth protecting (Figure 28). Considering the many working waterfronts that these areas comprise, it would be pragmatic to come up with strategies for habitat restoration and fisheries management that are mutually beneficial. Limiting boat dredging and promoting eelgrass beds in places where winter lobsters are known to reside, such as the Fore River of Portland (Heinig and Cowperthwaite, 1998) can strengthen the blue economy on the sides of both flora and fauna.

Steps like these embody the type of actions that should continue to be taken to improve understanding of eelgrass, such as through regular mapping efforts or outright protection. Building upon this, additional legal protections that ensure funding is allocated towards habitat restoration, combating invasive species, and promoting nature-based solutions that prevent polluted runoff from reaching the ocean can make a significant impact. Urban planners should strengthen regulations regarding polluting bodies and greater public outreach on the topic of seagrass's importance for biodiversity and carbon sequestration in the region should also be highlighted.

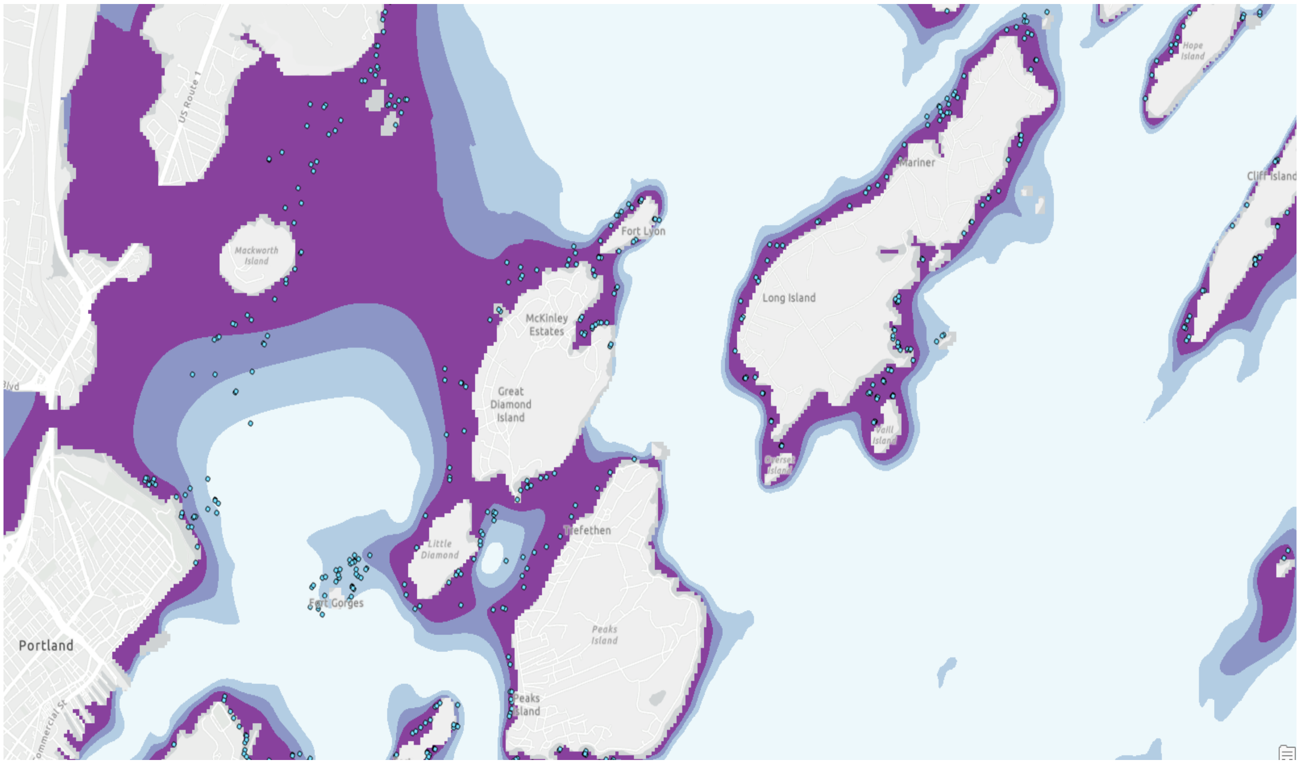

Figure 28: 1:30,000 map of nearshore Casco Bay, where the highest number of predicted and recorded eelgrass meadows were found. (Source: Author)

Future Work and Study Limitations

There are some limitations of note to this research project, particularly in the realm of data granularity. Because my primary source of data came from nineteen monitoring sondes around the Portland and Casco Bay area, there was a fair amount of interpolation and subsequent assumptions made about the environmental variables in between monitoring sites. In addition, because measurements of interest were captured on a weekly basis and the data used is specifically from the month of June 2022, there may be changes in sea surface temperature or other factors that are not reflected in the MaxEnt model.

The Emerging Hotspot Analysis, which was performed with the space-time cube and NetCDF file, was interesting as it showed the presence of oscillating and sporadic hotspots but should likely be taken with a grain of salt, as the temporal granularity of this study involves only three years. The minimum time slicing for an EHSA using the tool in ArcGIS was around 3 months, meaning there is insufficient granularity to draw any conclusions about whether the hotspots are insignificant, oscillating, or otherwise. However, this feature could be made much more insightful with the availability of more survey data from interim years to gauge whether certain seagrass meadows have shifted meaningfully in the last decade.

Another limitation included the number of variables included in the MaxEnt study. Even though I was able to incorporate five relevant covariates, even more of them would have been ideal. Data availability presented a challenge in this arena, and I was not able to locate sediment or wave energy data to contribute to this analysis. If included in the MaxEnt model, I imagine it would have clarified seagrass distribution further, as great shifts in my model output occurred after incorporating each variable, particularly bathymetric data – this makes sense because eelgrass generally cannot survive in deep waters at all, whereas other factors, such as temperature or salinity, may certainly contribute to whether or not a certain bed thrives or struggles, but does not present a similar binary outcome.

More directions I would have liked to take this thesis given enough time included a remote sensing component with machine learning models, such as unsupervised learning and Object-Based Image Analysis (OBIA). Broadly, OBIA is a method used in remote sensing that focuses on segmenting an image into meaningful objects instead of analyzing individual pixels. This approach is particularly useful for studying complex environments like eelgrass habitats, where similar-looking species, such as widgeon grass or sargassum, may lead to difficulties in classification (Society for Ecological Restoration, 2018).

Using OBIA could have given me a frame of reference for comparing what the MaxEnt predictive model "saw" as likely areas for seagrass meadows, compared to what the remote sensing analysis derived. There is verified information from the State of Maine regarding current seagrass meadows in polygon format and the results from the MaxEnt and OBIA eelgrass models in Casco Bay could have been compared to gauge the accuracy of these two approaches. This would likely have been carried out using ENVI software from L3Harris or possibly academic machine learning image processing algorithms. For example, a successful study on eelgrass modeling in Baja California used aerial imagery in conjunction with OBIA to estimate the probability of presence in local estuaries (Figure 29), illustrating an intriguing methodology.

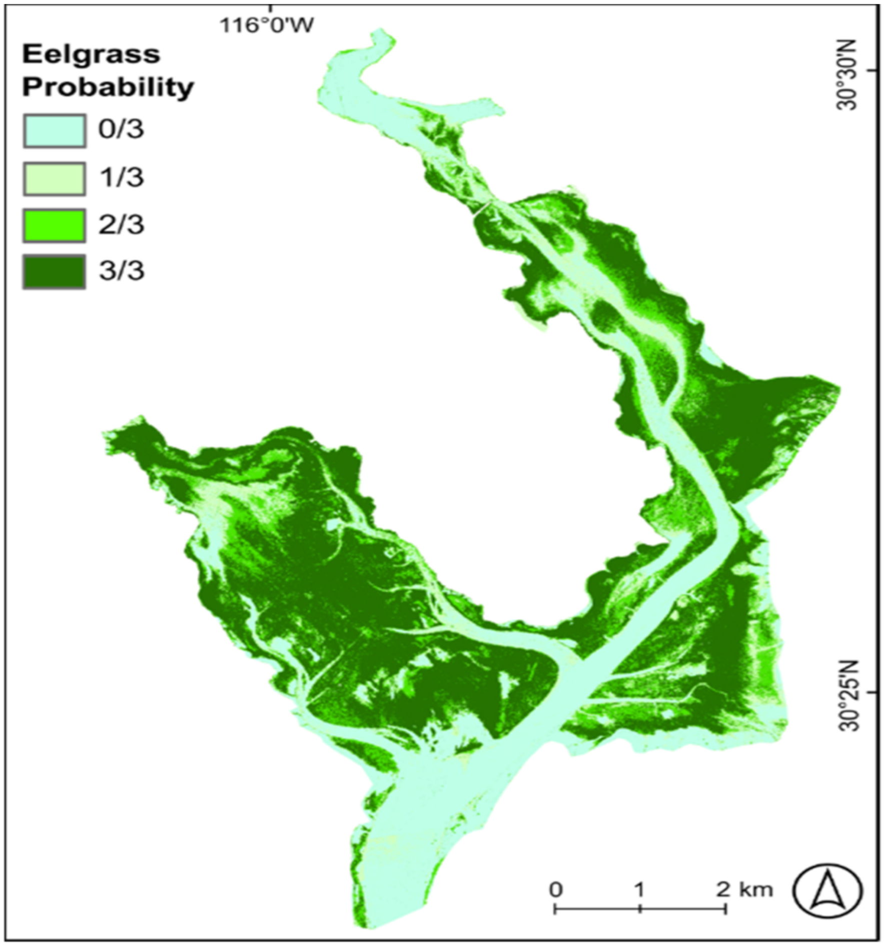

Figure 29: Predictive model of eelgrass in Baja California using OBIA. (Krause, et al. 2021)

Lastly, one more approach I would have liked to take – which would have been more on the applied ecology side – was surveying every site of interest in person through scientific dives. For example, because the MaxEnt model predicted high levels of seagrass coverage around Peaks Island and Mackworth Island, it would have been rewarding to physically document the seagrass levels in that region and ground-truth in a literal sense.

Chapter 6: Conclusion

Presence-only predictive modeling can be a promising step towards identifying future seagrass presence in Casco Bay. It allows this information to be cross validated with existing government data as well as satellite remote sensing orthoimagery. Implications of a successful MaxEnt model would include improving recommendations from policymakers regarding how best to protect seagrass.

Seagrass longevity in Casco Bay requires intervention to undo the anthropogenic harms done in years past. The exploratory spatial and preliminary predictive modeling of Zostera marina represents a longer work in progress but ideally provides some more information about what the current "state of seagrass" looks like in southern coastal Maine (Figures A2, A3) and how maximum entropy methods can reveal what may be in store for these pivotal blue carbon resources.

By identifying key environmental factors and areas of likely presence, this research can inform targeted conservation efforts. Conservation strategies should focus on protecting high-likelihood and suitability areas identified by the model, implementing measures to offset detrimental factors such as invasive species or excessively high ocean temperatures. Restoration projects should prioritize regions with high habitat suitability but current low eelgrass presence, as these areas have the potential for successful reestablishment of eelgrass meadows.

Continued monitoring of eelgrass populations and environmental conditions is essential for adaptive management. Regular data collection and analysis, as the Casco Bay Estuary Partnership and Friends of Casco Bay have been doing, will enable the detection of changes in eelgrass distribution and health, allowing for timely interventions. Adaptive management strategies should be flexible and responsive to new information, incorporating the latest research findings and technological advancements. This approach will ensure that conservation efforts remain effective in the face of dynamic environmental conditions and emerging threats.

The policy implications of this research are significant. Policymakers should leverage the findings to support the development of regulations and policies that protect eelgrass habitats. This could include the establishment of national marine sanctuaries, as Stellwagen Bank in coastal Massachusetts was and is still the only sanctuary in New England (Quintrell, et al. 1995). In regions that may be identified as high-suitability, restrictions on activities that contribute to increased pollution or damage to eelgrass beds, and incentives for sustainable coastal development practices should be implemented. Policies should also promote collaboration between government agencies, research groups, and local communities to ensure comprehensive conservation efforts.

Furthermore, integrating eelgrass conservation into broader climate resilience strategies is crucial. As eelgrass meadows play a vital role in carbon sequestration and shoreline protection, their preservation can contribute to mitigating the impacts of climate change. Policies that recognize and support the ecosystem services provided by eelgrass habitats will be essential for sustainable coastal management and climate adaptation efforts. Protecting these blue carbon habitats aligns with broader resilience strategies, emphasizing the need for policies that support the preservation of eelgrass meadows as part of climate change mitigation efforts.

Additionally, eelgrass provides essential habitat for a variety of marine species, including commercially important fish and shellfish. This makes eelgrass conservation vital for the health of working waterfronts, which depend on robust marine ecosystems for economic sustainability. By maintaining healthy eelgrass populations, the livelihoods of communities engaged in fisheries and aquaculture are supported, ensuring the long-term viability of these industries.

Future research should focus on refining the models by incorporating additional environmental variables and higher-resolution data and exploring the impacts of climate change. Utilizing aerial or high-resolution satellite imagery to build machine learning models also serves as a promising path integrating more traditional efforts with technological advancements. Continued monitoring and adaptive management, as always, will be essential to ensure the resilience of eelgrass habitats in Casco Bay and continue the legacy of these unsung heroes.

Eel-Grass, Edna St. Vincent Millay (1923)

No matter what I say,

All that I really love

Is the rain that flattens on the bay,

And the eel-grass in the cove;

The jingle-shells that lie and bleach

At the tide-line, and the trace

Of higher tides along the beach:

Nothing in this place.

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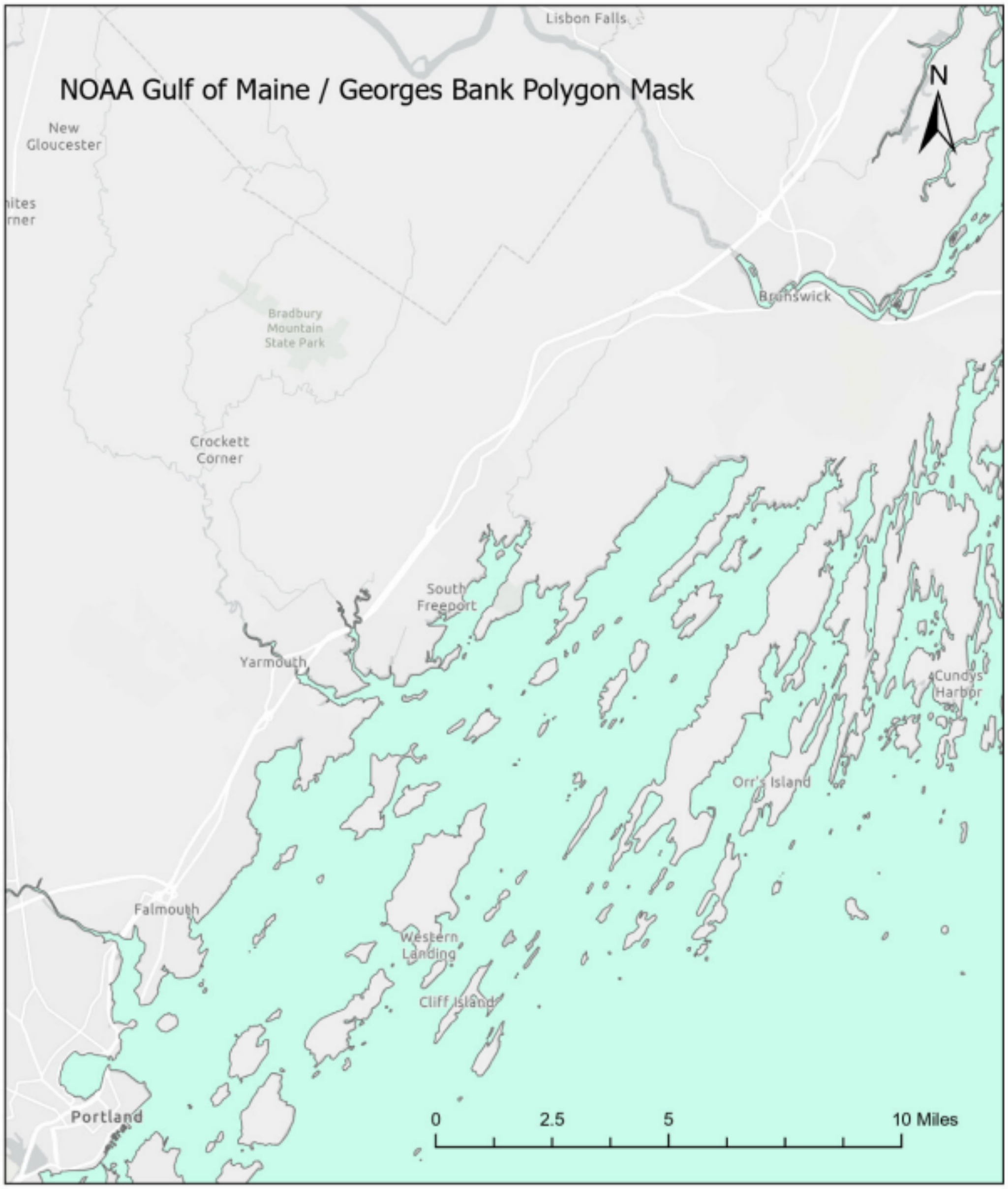
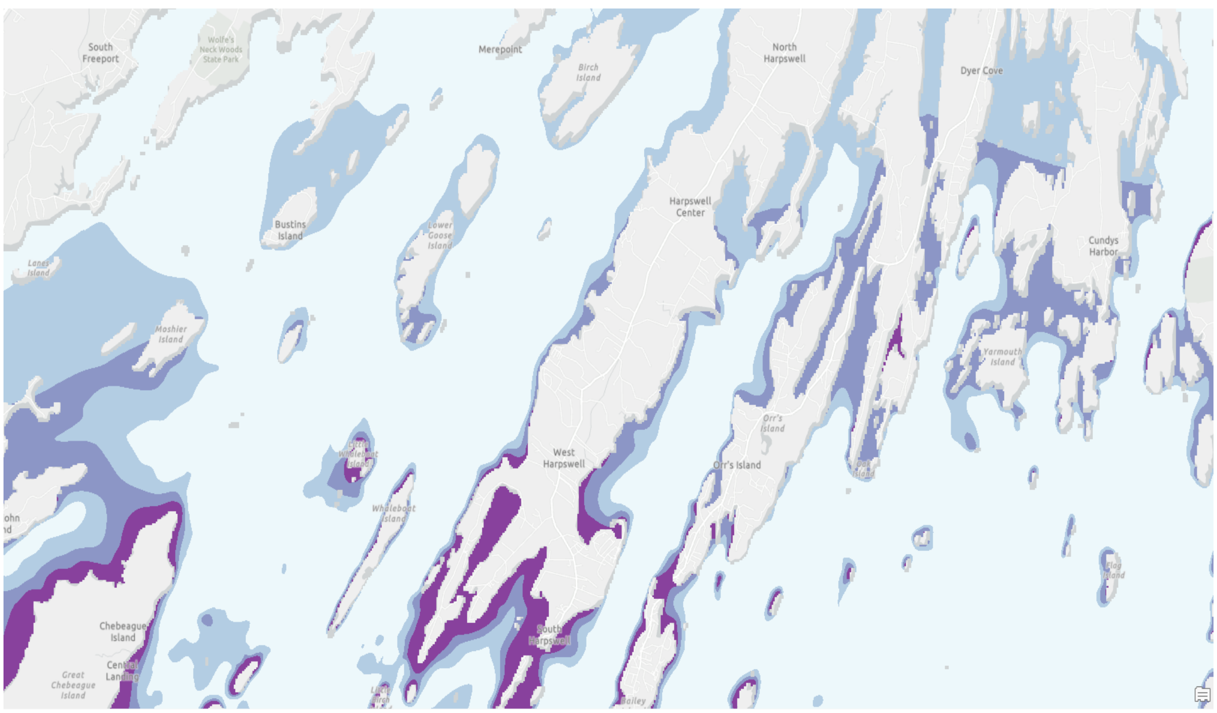
Appendix

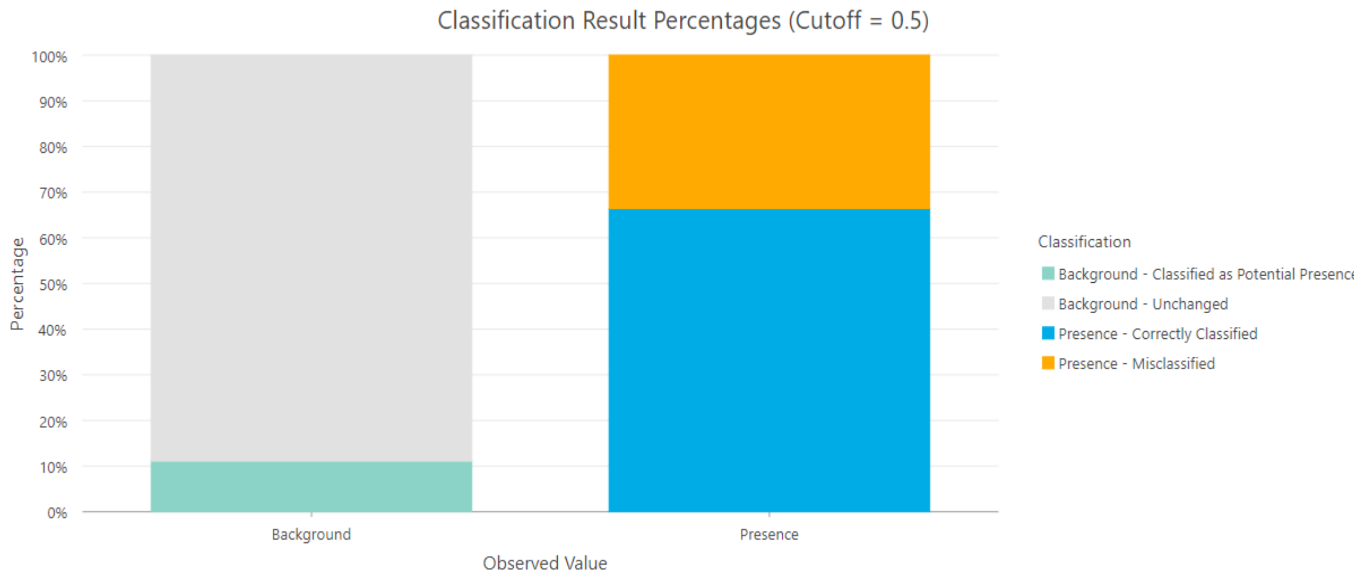


Appendix 1: Georges Bank / Gulf of Maine polygon mask.

Appendix 2: MaxEnt Results Zoomed In, 1:50,000 Scale (Portland)



Appendix 3: MaxEnt Results Zoomed In, 1:50,000 Scale (Harpswell)



Appendix 4: Classification Result Percentages (Source: Author)

Explanatory Variable Range Diagnostics

Training

Variable	Features	
	Minimum	Maximum
EBK_DO2	7.14	9.69
EBK_SALINITY	27.20	31.30
EBK_TEMPERATURE	12.23	18.85
TOPOTOR_BATH4	-6.87	71.95
EBK_TURBIDITY	0.40	6.47

Prediction

Match Variable	Rasters		
	Minimum	Maximum	Count outside training range (%)
EBK_DO2	6.63	9.69	1222 (0.22)
EBK_SALINITY	26.63	31.30	565 (0.10)
EBK_TEMPERATURE	12.23	18.85	0 (0.00)
TOPOTOR_BATH4	-6.87	71.95	0 (0.00)
EBK_TURBIDITY	0.40	6.47	0 (0.00)

Succeeded at Wednesday, May 1, 2024 4:28:17 PM (Elapsed Time: 11 minutes 14 seconds)

Appendix 5: MaxEnt Model Statistics (Source: Author)