A Site Selection Model for Eelgrass Restoration and Enhancement for Pleasant Bay, MA

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Introduction

Eelgrass (*Zostera marina* L.) is an angiosperm adapted to exist fully submerged in estuarine and marine environments. Eelgrass grows in shallow coastal waters and forms extensive meadows that provide essential ecosystem services throughout the temperate North Atlantic. Eelgrass meadows exhibit high primary and secondary production and are a significant global carbon sink, which is key to combatting global climate change (Fourqurean et al., 2012; Rohr et al., 2018; Novak et al. 2021). They also serve an important role in trophic transfer and export of nutrients via detrital matter to adjacent ecosystems (Thayer et al. 1984; Duarte and Cebrian 1996; Heck et al. 2008). In addition to their role in primary production, carbon storage, and export, eelgrass meadows serve as filters and improve water quality and clarity of coastal ecosystems through the direct trapping of suspended particles and the retention of organic matter (Short and Short 1984; Ward et al. 1984; Short et al. 2007). Meadows are also recognized for their high biodiversity, providing food and habitat to various organisms including microbes, invertebrates, and vertebrates such as fish and bay scallops, which in turn attract larger predators like bluefish and striped bass (Green and Short 2003).

Eelgrass is declining in many parts of its geographic range (Short et al., 2011; Krause-Jensen et al., 2020). The most ubiquitous anthropogenic threats have been eutrophication and suspended sediments from urban and agricultural runoff and aquaculture (Harlin and Miller 1981; Twilley et al. 1985; Short et al. 1987; Orth et al. 2006; Short et al. 2011; Krause-Jensen et al. 2020). Both eutrophication and sedimentation decrease the amount of light available to eelgrass for photosynthesis. Additionally, in systems with high nutrient loadings, epiphytes and fast-growing macroalgae outcompete eelgrass as they uptake nutrients more effectively and have relatively lower light requirements (Short et al., 1987). Other anthropogenic activities that have had direct impacts on eelgrass distribution by reducing water clarity and/or uprooting plants include dredge and fill, land reclamation, dock and jetty construction, and bottom disturbing fishing practices (Short and Wyllie-Echeverria 1996; Moore and Short 2006; Neckles et al. 2005). The direct loss of eelgrass by organisms other than humans has also occurred through overgrazing (e.g., geese), bioturbation, and disease (Short and Wyllie-Echeverria 1996).

Transplanting to restore eelgrass populations and mitigate loss has been used in many regions of the North Atlantic, achieving mixed success primarily because of poor site selection (Cunha et al. 2012; Short et al. 2002; van Katwijk et al. 2009; van Katwijk et al. 2016; Fonseca et al. 1998; Fonseca 2011). To improve the outcomes of costly transplant efforts, Short and colleagues (2002, 2005) developed a framework for quantitative site-selection based on scientific data from thriving eelgrass meadows and a literature review of the parameters that most influence eelgrass establishment and growth (Short et al. 2002; Short and Burdick 2005). The parameters are weighted according to their degree of influence on eelgrass success and combined in a multiplicative rating incorporating the various factors within a common index. The degree of suitability is reflected in the quantitative assessment. Specific sites with elements that are detrimental to eelgrass are eliminated from the analysis. The overall rating is compiled in GIS format and mapped to allow a quick overview of an area's potential for successful eelgrass growth. Field assessments and test-transplanting are then conducted at high-priority sites to confirm site suitability before performing a large-scale restoration (Short et al., 2002; Short and Burdick, 2005).

Pleasant Bay is a 9,000-acre estuary located in the Towns of Orleans, Chatham, Harwich and Brewster, Massachusetts. The estuary receives freshwater from northern and western shore tributaries and direct groundwater discharge. A narrow barrier beach forms the eastern shore of Pleasant Bay, and the estuary is connected to the Atlantic Ocean through two tidal inlets at its southern end, with the northernmost inlet having formed in April 2007. Due to its unique and extensive environmental values, the Bay and its surrounding shoreline and connected wetlands were designated by the Commonwealth as an Area of Critical Environmental Concern (ACEC). Eelgrass in this system is found in the low intertidal zone to approximately 3.5 m below mean low water with the greatest extent found in Little Pleasant Bay (LPB), which occupies the estuary’s shallow upper basin. Since 1951, eelgrass has declined by 55% due to increased nutrients and suspended sediments entering waterways from increased watershed development (PBA MEP, 2020). Notable areas where eelgrass has been wiped out by nutrient enrichment include Round Cove and Muddy Creek (PBA MEP, 2020).

For this project, we developed an Eelgrass Habitat Suitability Model in ArcGIS model builder to identify potential areas for restoration and enhancement (rehabilitation) activities. The model uses newly available data on eelgrass distribution and abundance, water quality and physical characteristics of the estuary and considers worse-case scenarios for sea-surface temperature (SST) increases.

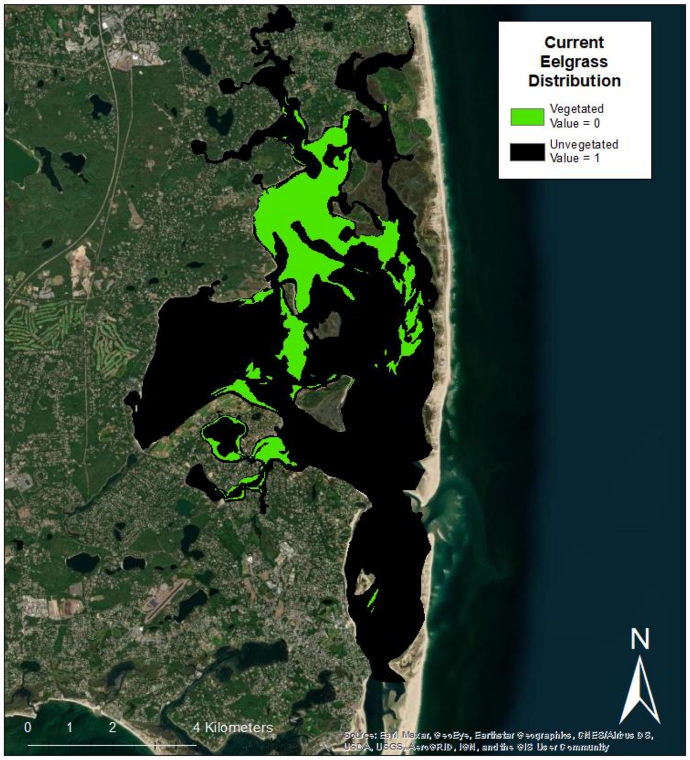
Methodology

Data inputs

The suitability of sites for restoration or rehabilitation was calculated by inputting multiple parameters that affect eelgrass establishment and growth and were available as geospatial data into a model created in ArcGIS 10.8.1 model builder. The model requires data to be in raster format and in the same coordinate system for analyses. The layers that were generated for the Pleasant Bay model include:

Current eelgrass distribution

The current distribution of eelgrass was obtained from recent mapping efforts conducted by Massachusetts Department of Environmental Protection (MADEP) in 2019 (MassGIS; Figure 1). In applying the current eelgrass distribution information to the model, areas currently vegetated were identified and eliminated from consideration (value= 0), all other areas were assigned a value of 1 and included as potential habitat for restoration.



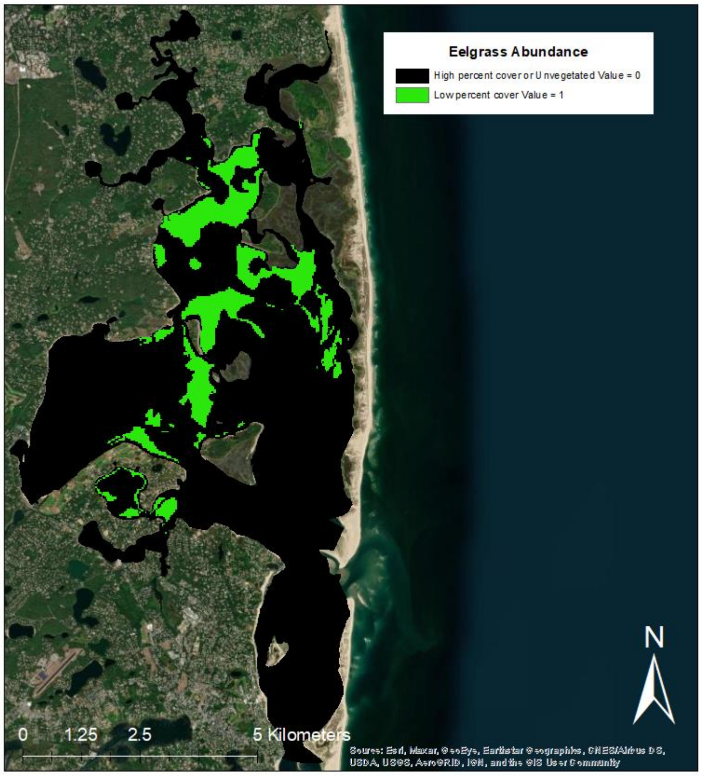
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. Map showing the distribution of eelgrass meadows in Pleasant Bay in 2019. Areas that are vegetated were eliminated from consideration and are denoted in green (value= 0) while unvegetated areas are denoted in black (value= 1).

Current estimates of eelgrass abundance

The National Park Service conducted bay-wide assessments of seagrass abundance during the summer of 2022. The assessments followed a randomized-tessellation stratified design in which a grid of tessellated hexagons served as the basis for random station selection. Sampling has been conducted every three years since 2006. At each of the roughly 200 stations sampled each year, estimates of percent cover were conducted at four locations using 0.25-m^2 quadrats.

The percent coverage data was used in our model to identify locations that are currently vegetated but have low percent coverage (<25%) and could potentially be rehabilitated. All areas with low percent coverage were assigned a value of 1 and included as potential habitat to prioritize for rehabilitation (Figure 2).



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2. Map showing the abundance of eelgrass meadows in Pleasant Bay. Areas with low percent cover (<25%) were assigned a value of 1 while areas that are unvegetated or have percent cover >25% were assigned a value of 0.

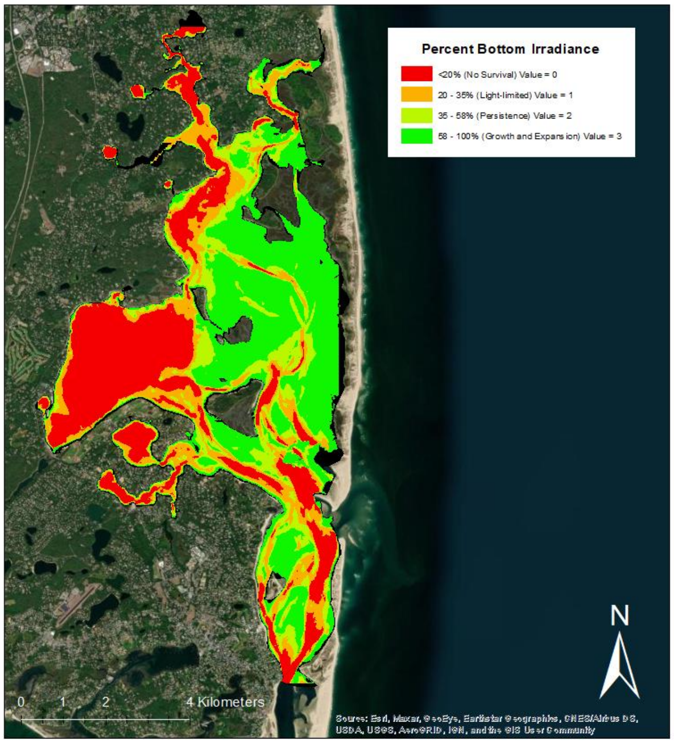
Light availability

Light is considered the most important factor governing the survival, distribution and abundance of eelgrass. The main contributors to light attenuation in the water column are turbidity, phytoplankton, and dissolved organic matter. Light attenuation (Kd) data (2007-2021) collected by the National Park Service's Inventory and Monitoring Program at 27 locations throughout Pleasant Bay was used to calculate median Kd across all sampling years. The median Kd was then applied to the Beer-Lambert's Equation to calculate percent irradiance reaching the bottom (Equation 1).

$$\text{Percent Bottom Irradiance} = 100*\text{EXP}(\text{Median Kd}*\text{Bathymetry NAVD88}) \quad (1)$$

For the model, the percent bottom irradiance point data was used to create a surface map of Pleasant Bay from the inverse distance weighting function (IDW). The data was then reclassified and ranked using surface irradiance threshold values from the literature (Dennison et al., 1993; Ochieng et al., 2010; Figure 3):

1) 0-20% (No Survival; value= 0)
2) 20-35% (Light Limited; value= 1)
3) 35-58% (Persistence; value= 2)
4) 58-100% (Growth and Expansion; value = 3)

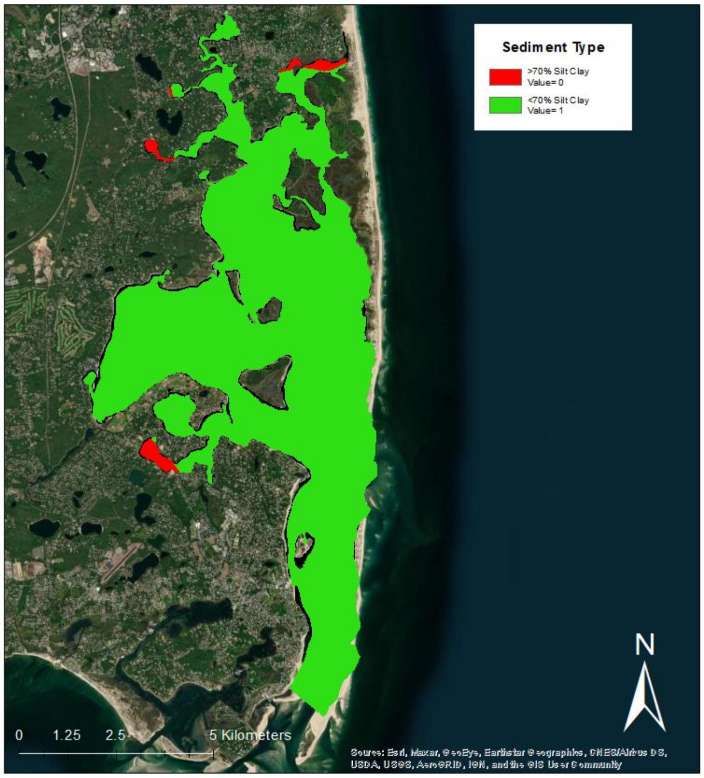


Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3. Map showing the range of percent bottom irradiances for Pleasant Bay. Areas are ranked (0 – 3) according to their suitability for the establishment and growth of eelgrass.

<u>Sediment type</u>

Sediment grain size is an important variable influencing eelgrass growth (Kenworthy and Fonseca 1977; Short 1987, 1993). Recent data on the spatial distribution of sediment was acquired from Center for Coastal Studies (Borelli, 2019). The data set was converted to a raster format and recoded. Areas >70% silt/clay received a value of 0 while areas that are cobble-free with <70% silt-clay received a value of 2, as this is the preferred sediment type for eelgrass restoration (Figure 4).



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4. Map showing areas that are >70% silt/clay (value= 0) and areas that are cobble-free with <70% silt-clay (value= 1).

Eelgrass distribution with 1.95°C SST increase

Increased water temperature from global climate change is predicted to exacerbate existing stresses to eelgrass meadows throughout the northeast, possibly leading to declines in populations. USGS recently developed a model to estimate how seagrass distribution and abundance in Pleasant Bay will likely change with expected temperature increases under various climate-change scenarios. Long-term seagrass and water quality monitoring data along with satellite temperature data were used to generate the spatial distribution of environmental drivers across the bay. These data were then used in a 0-D point-model that incorporated both empirical and mechanistic relationships to predict future spatial seagrass distribution and abundance from a depth range of 0.5 m to 3.5 m assuming increases of up to 1.95°C by the year 2050 (Carr et al. 2023). A current and wave orbital velocity (WOV) mask was then applied to the output to exclude areas where currents were too strong (i.e., greater than 1 ft s^{-1}) and regions where WOV exceeded 1 ft s^{-1} for more than 10% of the time.

In applying the USGS results to our model, areas predicted to be unvegetated were eliminated from consideration and assigned a value= 0 while areas predicted to have > 1.0 g/m^2 of biomass were assigned a value of 1 and included as potential habitat to prioritize for restoration (Figure 5).

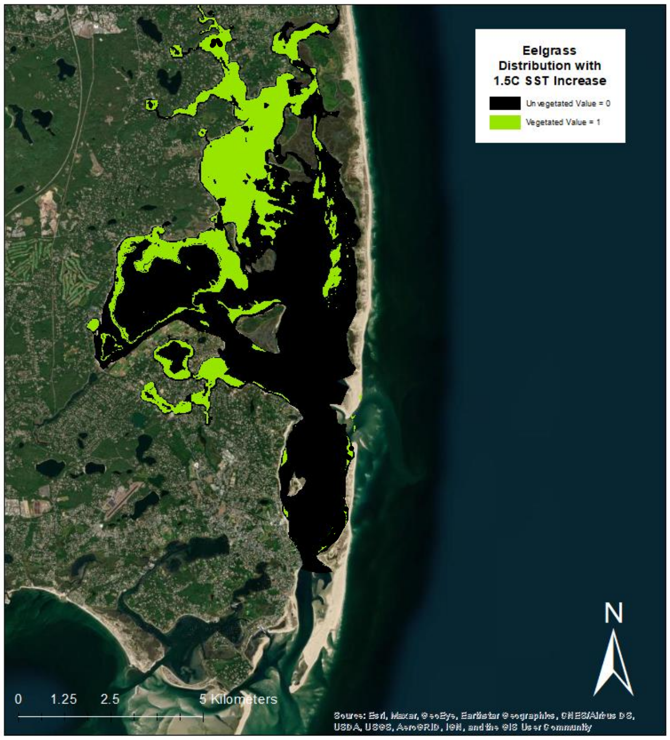


Figure 5. Map showing the predicted distribution of eelgrass meadows in Pleasant Bay assuming an increase in SST of 1.95°C by the year 2050. Areas that are unvegetated were eliminated from consideration and are denoted in black (value= 0) while vegetated areas are denoted in green (value= 1). *Please note that the predicted distribution of eelgrass is greater than the current distribution in 2019.

Conflicting uses

Information on the location of docks and piers, moorings, and aquaculture sites was obtained from MassGIS (2019). All types of conflicting uses are considered unsuitable habitat for transplanting eelgrass since they can fragment beds and/or cause declines. For example, docks and piers can reduce light availability to plants, traditional mooring chains (as opposed to conservation moorings) can uproot plants, and aquaculture sites are prone to disturbance via digging (Burdick and Short, 2009).

In applying the conflicting uses information to our model, all areas with mooring, docks, piers, and aquaculture activity were eliminated from consideration and assigned a value= 0 while all other areas in the system were assigned a value of 1 and included as potential habitat to prioritize for restoration or rehabilitation (Figure 6). However, in our final maps we show the locations of potential sites for restoration and rehabilitation both inside and outside of conflicting use zones so decisionmakers can easily identify the location and amount of area that is being lost to conflicting uses in case there are management actions that can be implemented.

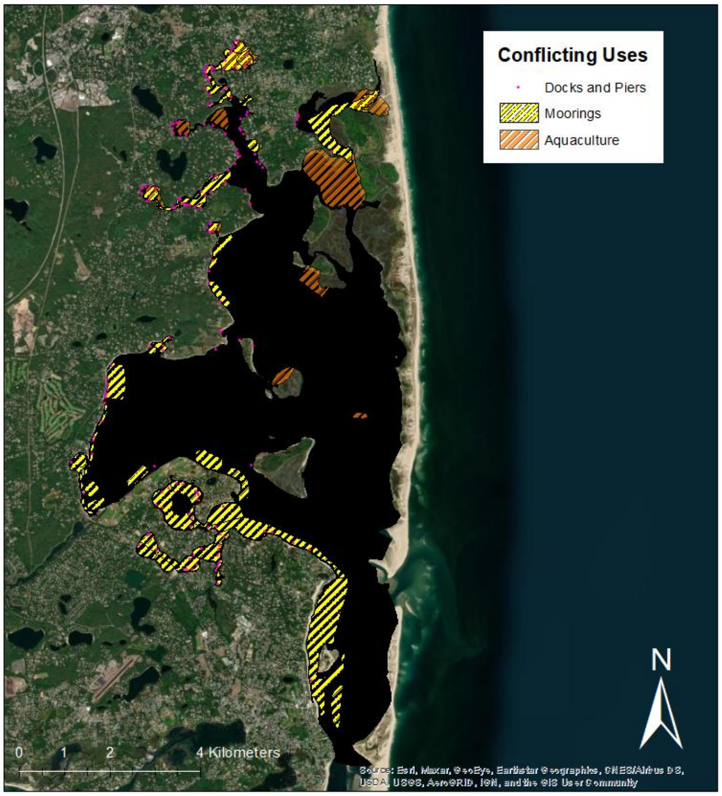


Figure 6. Map showing the locations of docks and piers, mooring fields, and aquaculture sites. Areas with these conflicting uses were eliminated from consideration (value= 0) while all other areas in the system were assigned a value of 1.

Water Quality

Information on total dissolved nitrogen (DIN), Total N, Total algal pigment, phosphate, and dissolved oxygen were obtained from Pleasant Bay Alliance (PBA, 2018). Each of these parameters have been continuously measured since MADEP established a TMDL for this system in 2007 based on bioactive nitrogen. The information was not used in the model due to its low resolution. Rather, the information was used to guide management options (Figure 7).

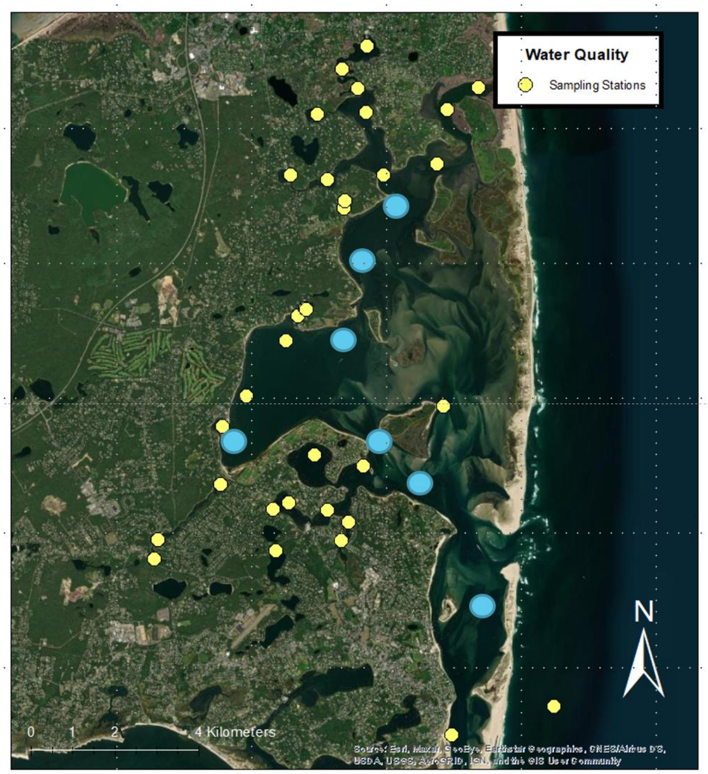


Figure 7. Map showing the locations of sampling sites where PBA measures water quality parameters associated with nutrient loading and eutrophication. Sites highlighted in blue indicate where water quality is improving.

GIS model development and calibration

Each raster layer was used in AcrGIS 10.8.1 model builder to calculate an overall Eelgrass Habitat Suitability Index for two scenarios. The first scenario identified sites for future restoration activities that are not currently vegetated but are predicted to be suitable for eelgrass under an SST increase of 1.95°C. The final output for the first scenario is the product of all the reclassified layers minus the current eelgrass abundance layer (current eelgrass distribution, light availability, sediment type, predicted eelgrass distribution assuming an SST increase of 1.95°C and conflicting uses).

The second scenario identified sites for immediate rehabilitation activities that had low eelgrass abundance (<25%) in 2022, are currently vegetated, and receive more than 20% SI. The final output layer incorporated the eelgrass abundance and distribution, light availability, and conflicting uses layers.

Both output results were reclassified into four categories based on their scores. Sites with the highest score (3) were considered "Most Suitable" for undertaking eelgrass restoration or rehabilitation. Areas with a moderate score (2) were considered "Very Suitable" and areas with low scores (1) were considered

"Suitable." Areas with a score of 0 were considered "Unsuitable" for eelgrass restoration or rehabilitation.

Phase II Reconnaissance

At sites rated as Most or Very Suitable, we will collect additional information on factors that may adversely impact eelgrass restoration success such as bioturbation potential (numbers of green crabs, clam worms, spider crabs, horseshoe crabs, etc.) and assess conflicting uses (aquaculture areas, moorings, anchor scars, lobster pots, etc.) to identify locations where management actions could help facilitate recovery. We will survey 10 of these sites during the summer of 2023.

Results

We simulated two scenarios using multiple parameters that influence the establishment of eelgrass. The first scenario identified multiple high priority sites with a rating of 3 (total area of 69 ha or 171 ac) for future restoration activities that are not currently vegetated but are predicted to be suitable for eelgrass under an SST increase of 1.95°C. The model also identified moderate priority sites with a rating of 2 (total area of 76 ha or 187 ac), and low priority sites with a rating of 1 (total area of 109 ha or 270 ac; Figure 8a; Table 1). Because some priority sites are also located in areas containing conflicting uses (dock and piers, mooring fields, and aquaculture) we also created a map and calculated the amount of area available for restoration outside of conflicting use zones (Figure 8b; Table 1).

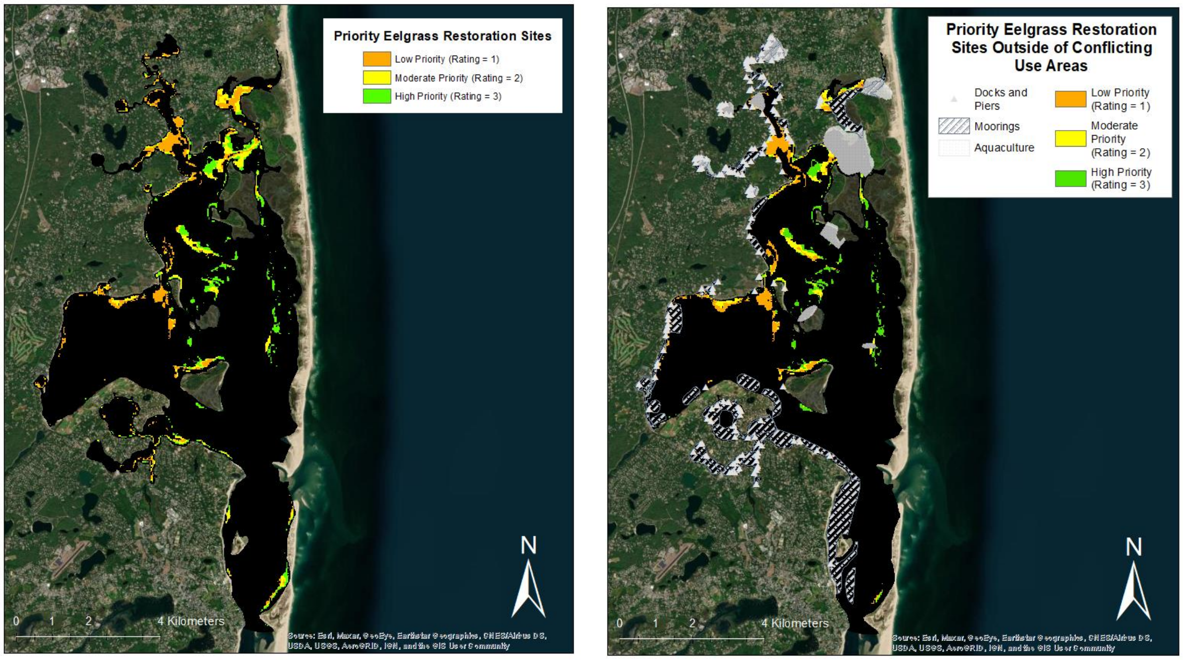


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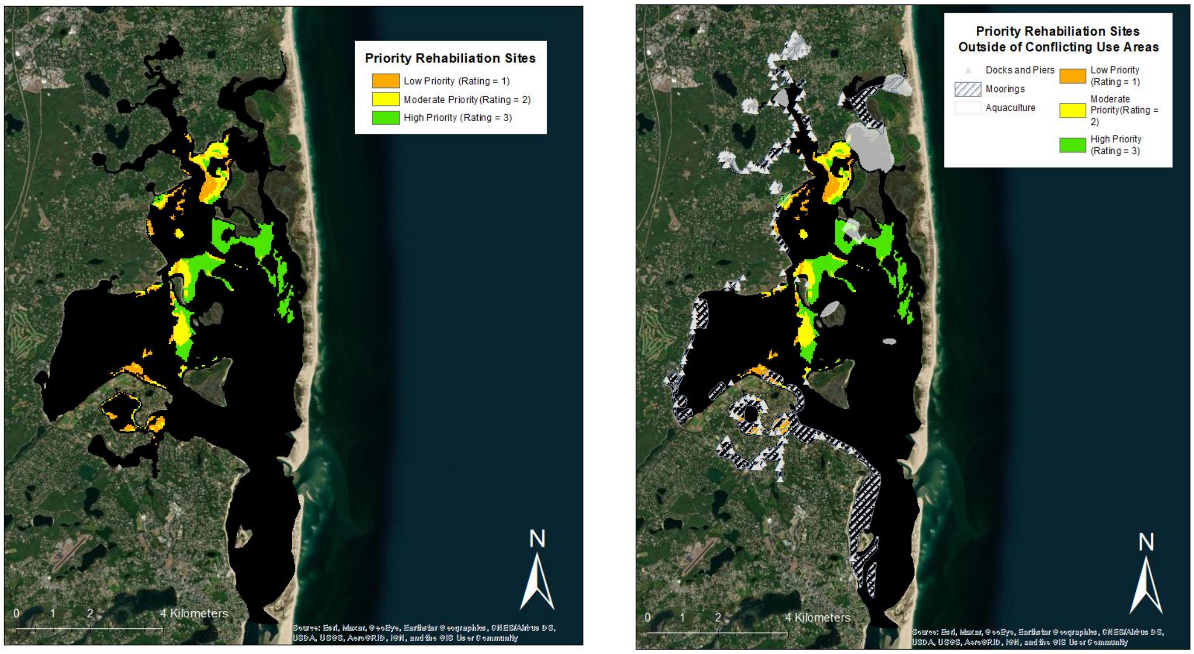
Figure 8. a) Map showing the locations of sites for potential restoration assuming an increase in SST of 1.95ºC as well as b) the location of priority sites not located in conflicting use areas.

Table 1. *Calculated areas for potential restoration assuming an increase in SST of 1.95ºC.*

Category	**All Sites**	**Sites outside of Conflicting Use Areas**
Low priority: rating = 1	109 ha (270 ac)	66 ha (162 ac)
Moderate priority: rating = 2	76 ha (187 ac)	41 ha (100 ac)
High priority: rating = 3	69 ha (171 ac)	46 ha (113 ac)

The second scenario identified sites for rehabilitation that receive > 20% SI and have low percent cover (<25%). There were multiple high priority sites identified for future rehabilitation with a rating of 3 (total area of 55 ha or 137 ac). The model also identified moderate priority sites with a rating of 2 (total area of 75 ha or 186 ac), and low priority sites with a rating of 1 (total area of 136 ha or 327 ac; Figure 9a; Table 2). Because some priority sites are also located in areas containing conflicting uses (dock and piers, mooring fields, and aquaculture) we also created a map and calculated the amount of area available for rehabilitation outside of conflicting use zones (Figure 9b; Table 2).



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 9. a) Map showing the locations of sites for potential rehabilitation with moderate to high light availability; b) the location of priority rehabilitation sites not located in conflicting use areas.

Table 2. *Calculated areas for potential rehabilitation*.

Category	**All Sites**	**Sites outside of Conflicting Use Areas**
Low priority: rating = 1	55 ha (137 ac)	40 ha (99 ac)
Moderate priority: rating = 2	75 ha (186 ac)	68 ha (167 ac)
High priority: rating = 3	136 ha (327 ac)	119 ha (294 ac)

Discussion

Pleasant Bay is currently vegetated with 433 ha (1,070 ac) of eelgrass. This is 55% less than was present in the 1950s. We developed a site selection model to prioritize sites for restoration and rehabilitation using multiple scenarios and identified an area larger than the current extent of eelgrass (520 ha; 1,285 ac). The first scenario identified sites for future restoration activities assuming an SST increase of 1.95^{o}C. The second scenario identified sites for rehabilitation activities that are not light-limited and currently have low eelgrass abundance.

The first scenario identified multiple high priority sites for restoration with a rating of 3 (total area of 69 ha or 171 ac). The model also identified moderate priority sites with a rating of 2 (total area of 76 ha or 187 ac), and low priority sites with a rating of 1 (total area of 109 ha or 270 ac; Figure 8a; Table 1; Supplemental Figure 1). The majority of the high priority sites are located in three regions: 1. between Barley Neck, Pochet Island and Sampson Island; 2. east of Nauset Beach, west of Sipson Island; and 3. between Sipson Island and Hog Island within Little Pleasant Bay. Unfortunately, some of these high priority sites are also located in areas containing conflicting uses (Figure 8b; Table 1; Supplemental Figure 2) and should be avoided unless a management activity is implemented to ensure restoration success (see management options below).

The second scenario identified sites for rehabilitation that receive > 20% SI and have low percent cover (<25%). There were multiple high priority sites for rehabilitation with a rating of 3 (total area of 55 ha or 137 ac), moderate priority sites with a rating of 2 (total area of 75 ha or 186 ac), and low priority sites with a rating of 1 (total area of 136 ha or 327 ac; Figure 9a; Table 2; Supplemental Figure 3). The majority of the high priority sites identified for rehabilitation are located in between and west of Hog Island and Sipson Island in the system and only a few areas were also located in areas containing conflicting uses (Figure 9b; Table 2; Supplemental Figure 4).

There was an adequate amount of information available for the development of model to support both scenarios. We had current bay-wide eelgrass distribution and abundance data, as well as light and sediment. Bathymetry and wave exposure information were also incorporated via the USGS model results predicting future temperature conditions in the system. In addition, we received information on conflicting uses (docks and piers, moorings, and aquaculture) to include in our final maps as these areas may influence eelgrass transplant success. Water quality information was lacking in spatial resolution to incorporate it as a layer in the model. However, it is unlikely that higher resolution data would influence the output for each scenario.

High failure rates of eelgrass restoration projects will persist if appropriate site selection standards and metrics are not applied (Fonseca, 2011). Though many variables may contribute to seagrass presence or absence, modeling those critical to restoration in a particular area can maximize the potential for success. Furthermore, from a management perspective, it is often more feasible to measure and monitor those variables that can be removed or improved to facilitate restoration success. Now that multiple areas have been prioritized for restoration and rehabilitation, we strongly recommend continuing to "Phase II" of the site selection process as described in Short et al. (2002). Phase II involves evaluating sites with high scores by conducting a test transplanting effort. The survival of test transplants is highly indicative of eelgrass habitat suitability and provides the best indication of how well a large-scale transplanting effort will succeed at a given site. For Pleasant Bay, we recommend using the results of scenario 1 (Figure 8; Supplemental Figures 1 and 2) and test-transplanting vegetative shoots and seeds at multiple sites with a score of 3 to evaluate eelgrass habitat suitability for restoration. Sites within conflicting uses should be avoided. For rehabilitation, we recommend using the results of scenario 2 (Figure 9; Supplemental Figures 3 and 4) and seeding at multiple sites with a score of 3 and outside of conflicting use zones.

Management Options

Our study provides important information on where to target restoration and rehabilitation efforts in Pleasant Bay. It is apparent that eelgrass in these systems is exposed to high nutrient loading from fertilizers and sediments, as well as water temperatures that can inhibit growth and/or survival. As the climate continues to warm, eelgrass in the harbors will continue to be exposed to increased water temperatures and periods of thermal stress. However, eelgrass can survive if other environmental parameters that promote growth and expansion are optimal/or and effective management strategies are developed. Below are some options for potential management actions that have been shown elsewhere to improve eelgrass health and facilitate recovery in the harbor.

First and foremost, water quality within Pleasant Bay needs to continue to improve by reducing land-based pollution and decreasing nutrient and sediment run-off, reducing or eliminating the use of fertilizers and persistent pesticides and increasing filtration of effluent. The reduction in nutrients within the system will lead to a reduction in nuisance algae which limit the amount of light available to eelgrass for growth. Moreover, if plants are no longer light-stressed they will be able to tolerate longer periods of thermal stress caused by climate change. To achieve this objective, Pleasant Bay can continue to implement/develop public education programs that identify actions that individuals can take to improve water quality and reduce stresses on eelgrass in the system. For example, individuals can help reduce threats to water quality by preventing pollutants (e.g. fertilizers, paint, gasoline, solvents and garden chemicals) from entering storm-water drains. To reduce sediment and nutrient run-off into waterways, individuals can maintain vegetation on creek banks and shorelines adjacent to the harbor, create retention ponds or ditches to reduce high-discharge flows or plant a buffer strip of plants in these areas. In addition, homeowners could upgrade septic systems by retrofitting septic tanks with advanced pre-treatment, recirculating aerobic treatment units, or replacing traditional septic tanks with upgraded nutrient-reducing technology.

In addition to improving water quality, managers can continue to monitor existing eelgrass meadows in the harbor using a hierarchical framework to detect and predict changes so that appropriate management strategies can be developed. The monitoring approach would include three tiers that are integrated across spatial scales and sampling intensities (see Neckles et al. 2012). Tier 1 monitoring would involve mapping eelgrass in Pleasant Bay every three to five years to provide large-scale information on seagrass distribution and meadow size. Tier 2 monitoring involves conducting bay-wide, quadrat-based assessments of eelgrass percent cover and canopy height at permanent sampling stations following a spatially distributed random design. Tier 3 monitoring involves continuing high-resolution measurements of seagrass condition (percent cover, canopy height, total and reproductive shoot density, biomass, and seagrass depth limit) at a representative index site in the system.

Lastly, raising awareness about the socio-economic and ecological values of eelgrass is critical in building support for seagrass conservation. Engaging local communities and stakeholders is essential in any conservation strategy. Volunteer monitoring programs can be effective in increasing public awareness of the value of eelgrass meadows and the threats to their survival. Community monitoring programs, such as SeagrassNet, successfully promote stewardship, reinforce the value of eelgrass habitats and collect data about the condition of this species. Public education programs should identify actions that individuals can take to reduce stresses on eelgrass in this system. For example, boaters can avoid anchoring and running their propellers through eelgrass meadows. In addition, developing or expanding mooring fields that overlap with eelgrass meadows can be discouraged and/or those areas could be closed temporarily to allow meadows to self-rehabilitate. Traditional moorings could also be replaced with conservation moorings that have floating rodes that minimize or eliminate chain drag on the bottom.

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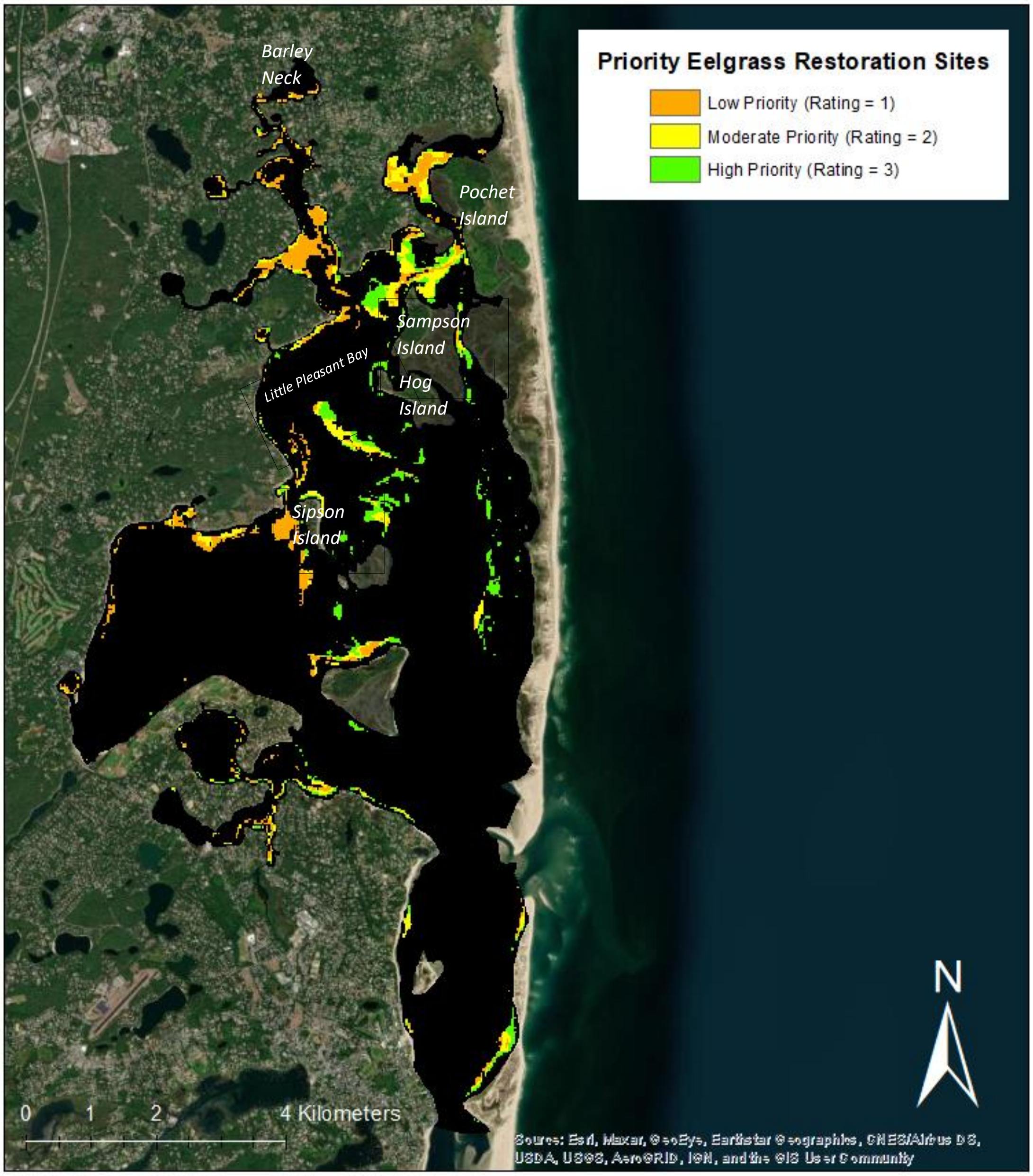
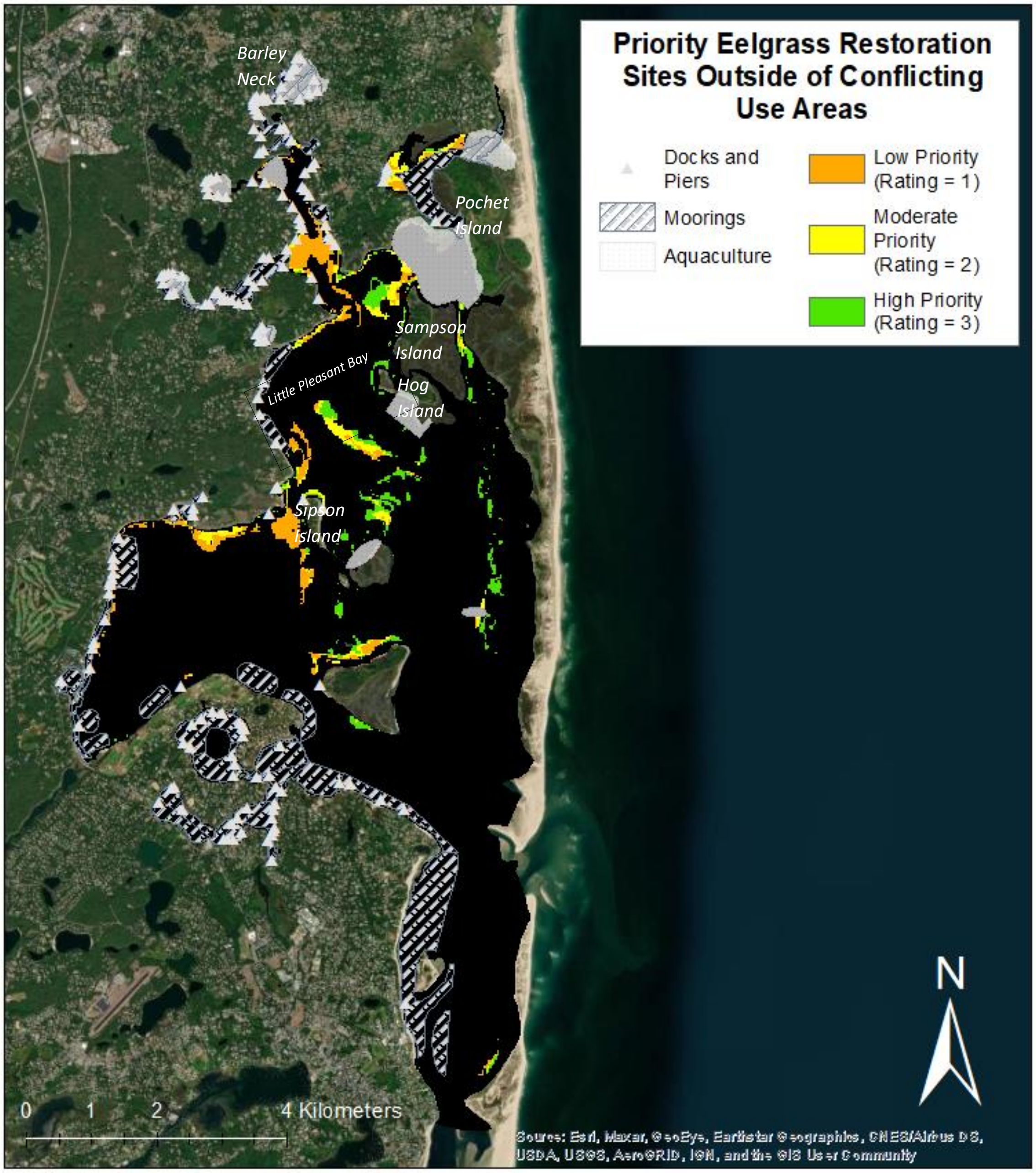
Supplemental Figure 1. Map showing the locations of sites for potential restoration assuming an increase in SST of 1.95^{o}C.



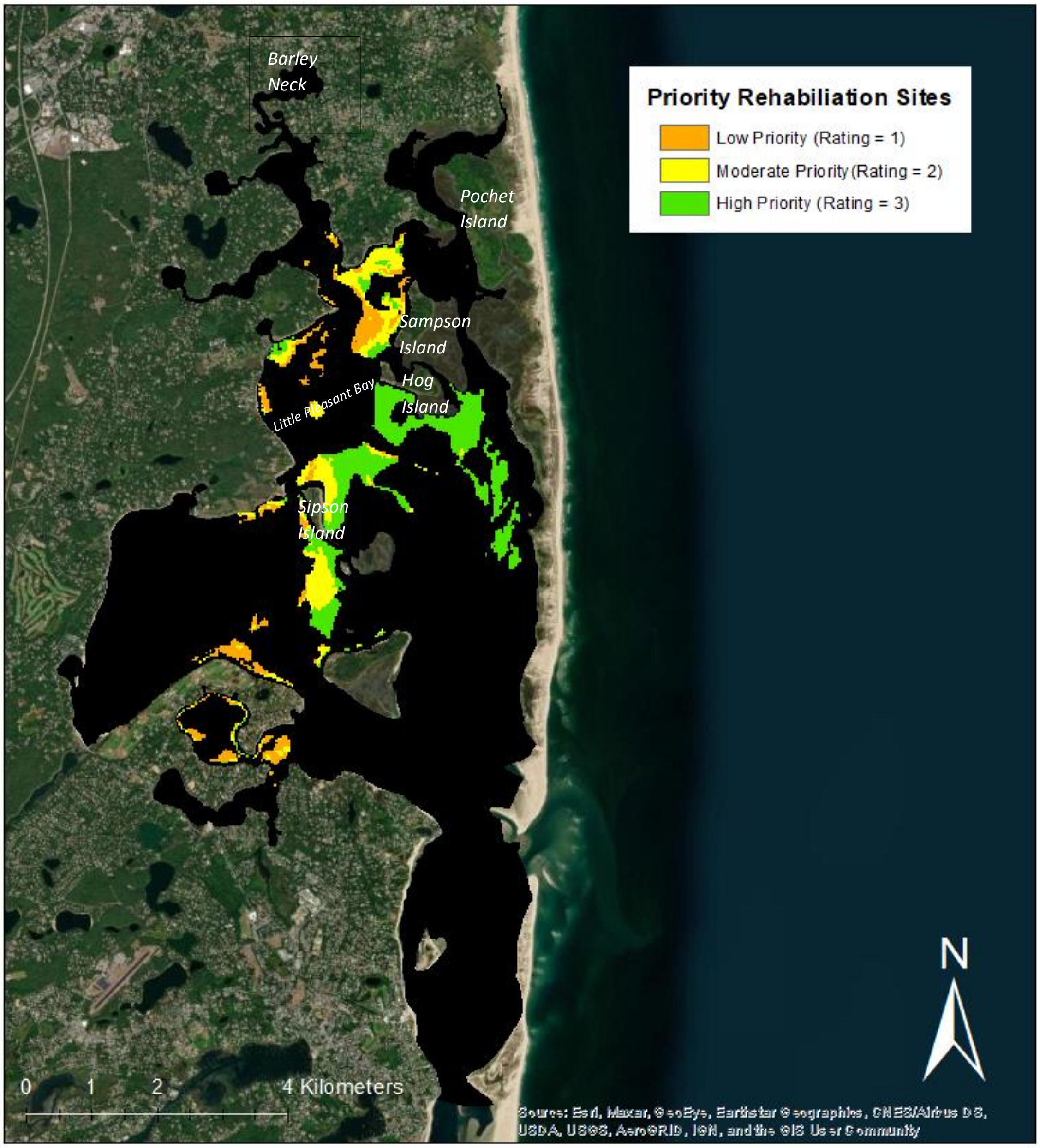
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Supplemental Figure 2. Map showing the locations of sites for potential restoration relative to conflicting use zones and assuming an increase in SST of 1.95°C.



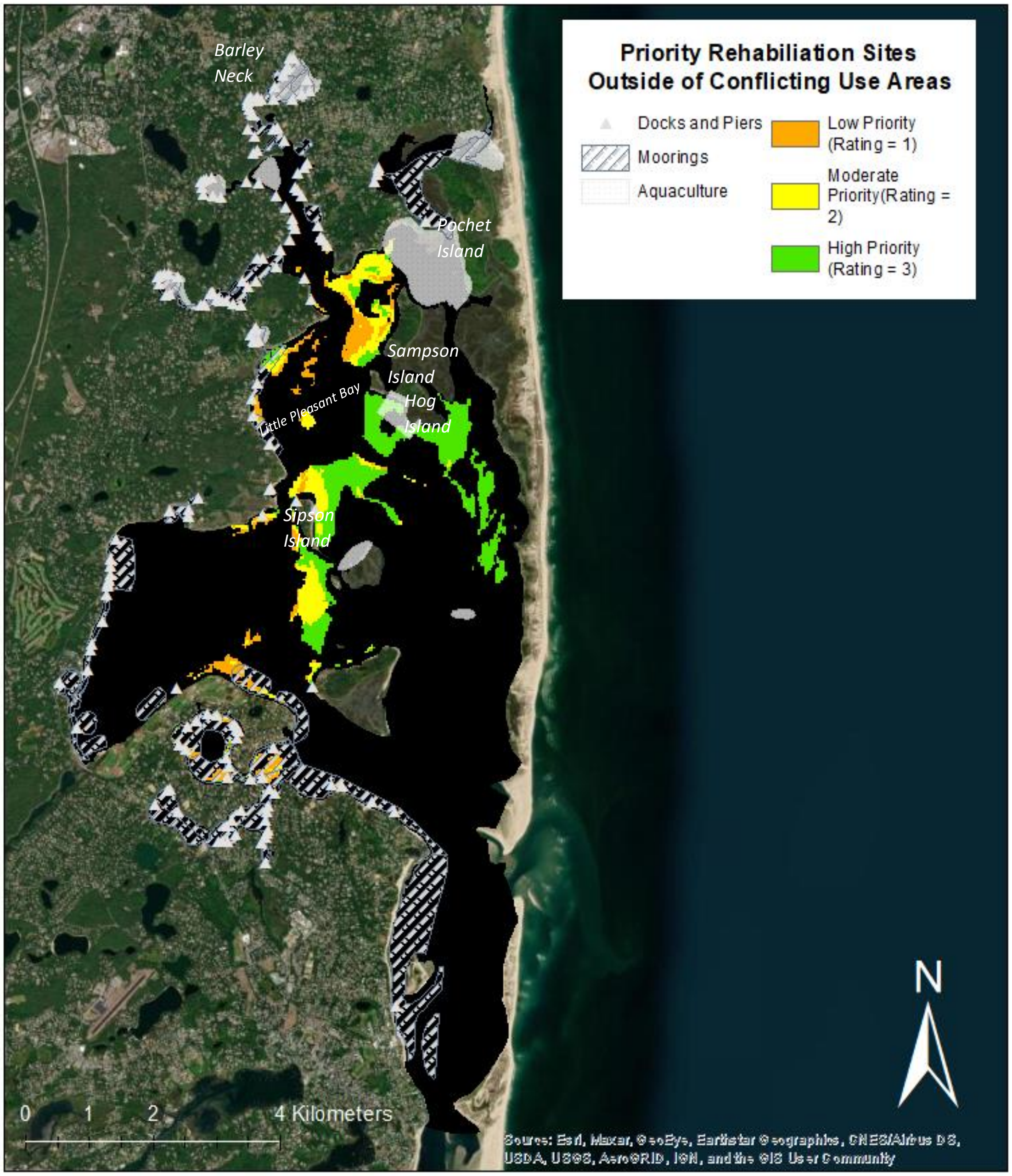
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Supplemental Figure 3. Map showing the locations of sites for potential rehabilitation.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Supplemental Figure 4. Map showing the locations of sites for potential rehabilitation relative to conflicting use zones.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community