A SPATIAL MODEL TO IDENTIFY AND PRIORITIZE POTENTIAL OYSTER REEF RESTORATION SITES ALONG THE GEORGIA COAST

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Abstract. The vast overharvesting of oysters during the early 1900s led to the 85% reduction of Georgia's oyster population. Oyster restoration has been gaining popularity in efforts to recover oyster populations and reestablish a sustainable fishery. Reef restoration success is dependent on locating sites based on a balance of physical, chemical, and biological factors. A challenge in restoring oyster reefs is that sessile adult oysters cannot escape adverse water quality conditions. Physicochemical water quality factors such as salinity, water temperature, and pH contribute to successful recruitment, survival, and overall success of restored reefs. Our objectives are to 1) build a framework to identify spatial patterns in physicochemical drivers of oyster reef success; 2) create a spatial index of oyster restoration suitability for Georgia coastal estuaries; and 3) prioritize identified restoration targets according to restoration suitability. Spatial data was obtained from the Georgia Department of Natural Resources CRD G-WRAP program and CRD shellfish water quality monitoring program. The data was used to build an oyster reef restoration suitability index for the Georgia coast. The index identified potential restoration sites based on our three focal physicochemical drivers as well as accounting for anthropogenic stressors. The index rated estuary habitat by combined parameter suitability. This research provides a baseline map for targeting future restoration locations along the Georgia coast while also providing a framework that can be applied or adapted to other geographic regions.

INTRODUCTION

The Eastern Oyster (*Crassostrea virginica*) has been vital to the culture, economy, and ecosystems of the Georgia coast dating back to the original colonial settlements (Harris 1980) . The introduction of oyster canneries at the turn of the 20th century, led to an increased economic value for *C. virginica.* From the late 1800s until the 1930s, Georgia led the nation with 13 oyster canneries (Manley, Power, & Walker 2008). The explosion of the oyster cannery industry contributed to extensive overharvesting of Georgia's oyster stock up until the end of the 1930s when the fishery collapsed, and canneries were no longer viable. Estimates indicate that as high as 90%-99% of the original worldwide oyster population has been lost with an 85% reduction of Georgia oysters (Beck et al. 2011; Georgia Department of Natural Resources 2013).

The massive reduction in oyster population has greatly impacted not only the coastal economy, but also the coastal ecosystems of Georgia (Harris 1980). *Crassostrea virginica* is regarded as one of the fundamental ecosystem engineers along the Georgia coast (Georgia Department of Natural Resources 2013). The reef structures produced by these bivalves are integral to the biodiversity of estuarine systems along the coast (Baggett et al. 2014). Oyster reefs provide an extensive source of hard substratum that is vital to the lifecycles of epibiotic invertebrates (Powers et al. 2009). Many important fishery species also rely on oyster reefs as vital nursery habitats, with some species living around the reefs throughout their entire lifespan (Zimmerman et al. 1989). Additionally, *C. virginica* contribute to improvement and maintenance of water quality with filtering rates as high as of 0.12 m^3 g^{-1} dry weight (DW) day^{-1} (Beck et al. 2011; Ehrich and Harris 2015).

The recognition of the ecological importance of *C. virginica* reefs in addition to the economic value of oyster fisheries, has led to a rapid increase in oyster restoration projects (Coen et al. 2007). These restoration projects have produced data on the key parameters which lead to oyster reef success (Baker and Mann 1992; Dekshenieks, Hofmann, and Powell 1993; Sheldon and Alder 2011; Baggett et al. 2014; Laakkonen 2014, Boulais et al. 2017).

Physicochemical drivers have been identified as vital factors for oyster reef success. Four commonly identified physicochemical drivers are salinity, temperature, pH, and dissolved oxygen (Baker and Mann 1992; Dekshenieks, Hofmann, and Powell 1993; Sheldon and Alder 2011; Baggett et al. 2014; Laakkonen 2014; Boulais et al. 2017). In addition to physicochemical drivers, anthropogenic stressors can greatly inhibit the success of an oyster reef (Wall et al. 2005; Georgia Department of Natural Resources 2013).

OBJECTIVES

Our objectives are to 1) build a framework to identify spatial patterns in physicochemical drivers of oyster reef success; 2) create a spatial index of oyster restoration suit-ability for Georgia coastal estuaries; and 3) prioritize identified restoration targets according to restoration suit-ability.

METHODS

Literature Review

Ideal ranges for salinity, water temperature, pH, and dissolved oxygen for *C. virginica* were identified through literature synthesis. However, dissolved oxygen was withheld from this model due to its ideal levels throughout the coast. Articles were cross referenced to confirm a proper range was applied. An emphasis was placed on articles that focused on *C. virginica* in the juvenile stage, particularly in the southeastern United States. Coastal water access points and armored shorelines were identified as anthropogenic stressors that would lead to decreased oyster reef success.

Data Collection

Physicochemical and anthropogenic stressor data was retrieved from the G-WRAP program via data query. The data retrieved from the G-WRAP program included salinity for 12 coastal rivers, coastal water access points, and armored shorelines. Additional physicochemical data was retrieved from the Georgia Department of Natural Resources CRD shellfish water quality monitoring program. The CRD physicochemical data included salinity, water temperature, and pH data collected at 64 testing sites along the Georgia coast. Data ranged over the years of 2017 and 2018. In 2017, data were collected at each site once each month with the exceptions of February, May, June, and December. Also, data were collected twice in the months of July and September. In 2018, data were collected at each site once a month.

ArcGIS Analysis

Salinity data collected for twelve coastal rivers were used as an input for the kriging spatial analyst tool and processed to the extent of an area of specific to each of the rivers (Childs 2004). The salinity, pH, and water temperature data from the 64 CRD water quality monitoring sites were used as inputs to the inverse distance weighted spatial analyst tool interpolation tool (Childs 2004). Each interpolation was reclassified into a low, medium, and high habitat quality rating (1-3) based off optimal ranges for each physicochemical parameter (Table 1). The three reclassifications from the shellfish water quality data were summed and then a quotient was found to produce a habitat quality score for the entire coast (Figure 1). A 50 m radius surrounding anthropogenic stressor sites were excluded from the final maps.

Table 1. Habitat quality ranges for each of the three identified physicochemical parameters. Low habitat quality includes values that fall out of the accepted range. Medium habitat quality includes values that lie at the extremes of the accepted ranges. High habitat quality includes values that fall in the middle of the accepted ranges. All accepted ranges are based off cross-referenced literature review. Salinity ranges were based off Dekshenieks, Hofmann, and Powell 1993; Baggett 2014; Laakkonen 2014. Water temperature ranges were based off Dekshenieks, Hofmann, and Powell 1993; Laakkonen 2014. pH ranges were based off Laakkonen 2014; Boulais et al. 2017.

Habitat Quality	Salinity (ppt)	Water Temp. (°C)	pH
Low	<14; > 28	10-17.5	7-7.35
Medium	14-16; 26-28	17.5-20	7.35-7.7
High	16-28	20-31	7.7-8.1

$$\frac{F_1 + F_2 + F_3}{n} = Habitat\ Quality\ Score$$

$$F_1 = Salinity\ Suitability\ Score$$

$$F_2 = Water\ Temperature\ Suitability\ Score$$

$$F_3 = pH\ Suitability\ Score$$

$$n = Number\ of\ Data\ Sets$$

Figure 1. Equation used to determine the habitat quality score for the physicochemical model. For this model, only three parameters were applied. Therefore, the n value equaled three. If more parameters were to be applied, the n-value would adjust accordingly.

RESULTS

River Salinities

Interpolation of the river salinity data highlighted a unique seasonal shift in salinity ranges from the spring to fall. During the spring, the optimal salinity range was closer to the mouth of the river where the fall showed a shift upriver for optimal salinity ranges. The Ogeechee River was selected to model this trend in detail while also displaying the effects of anthropogenic stressors (Figure 2).

Physicochemical Model

Following the inverse distance weighted interpolation of the CRD water quality physicochemical data, a map was produced for each parameter (Figure 3). The interpolation of the water temperature data showed much of the coast fell into the high habitat quality range. The only significant region of decreased water temperature habitat quality occurred around the mouth of the Altamaha River.

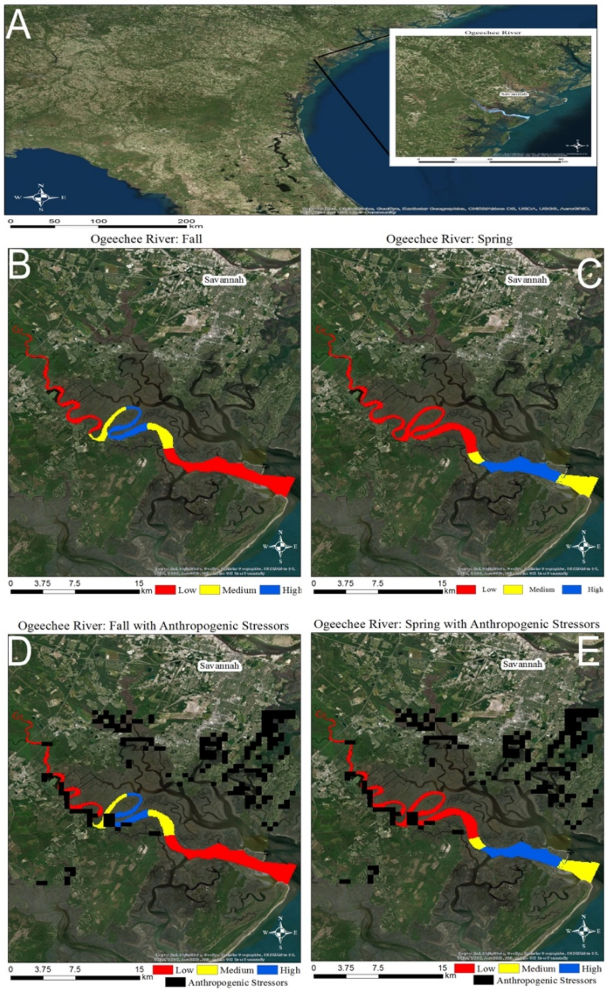

Figure 2. (A). Inset map detailing the location of the Ogeechee River in relation to the Georgia coast. (B) Salinity ranges during the Fall season without anthropogenic stressors. (C) Salinity ranges during the Spring season without anthropogenic stressors. (D) Salinity ranges during the Fall season with anthropogenic stressors. (E) Salinity ranges during the Spring season with anthropogenic stressors.

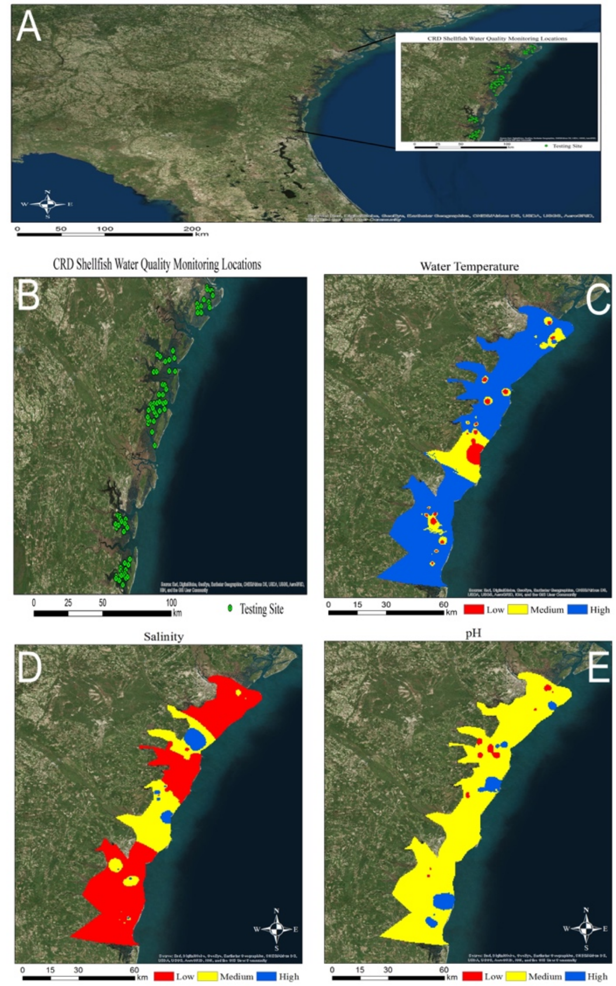

Figure 3. (A) Inset map of detailing the location of CRD shellfish water quality monitoring locations in relation to the Georgia coast. (B) Zoomed in view of CRD shellfish water quality monitoring locations to provide detailed context of the extent of the data set. Interpolation of the (C) water temperature data, (D) salinity data, and (E) pH data from the CRD shellfish water quality monitoring locations sites.

The interpolation of the salinity data displayed most of the coast in a low habitat quality region. The interpolation of the pH data lead to medium habitat quality for most of the coast. When these three interpolations were summed and normalized by the number of input data sets the physicochemical model showed a majority of medium habitat quality (Figure 4). There was only one distinct location throughout the coast that fell into the high habitat quality range. There were several areas of low habitat quality scattered throughout the coast. The addition of anthropogenic stressors into the model excluded additional areas from consideration as potential oyster reef restoration sites (Figure 4).

DISCUSSION

River salinity models display the dynamic nature of the Georgia coast by showing seasonal salinity shift. Incomplete physicochemical data prevents development of a full suitability index for oyster restoration in rivers. Therefore, acquisition of a full water quality dataset in the rivers should be a research priority for restoration pro-jects. Additionally, acquisition of hard substrate data would also improve the river model.

A question that has been raised by the river salinity models is if fresh groundwater flow from the marshes mitigate some of the high salinity ranges (low habitat quality) found at the seaward end of the rivers along the river banks (Craft 2007; Wilson et al. 2011). There are many oyster reefs that thrive in the low habitat quality regions found on the seaward end of the rivers.

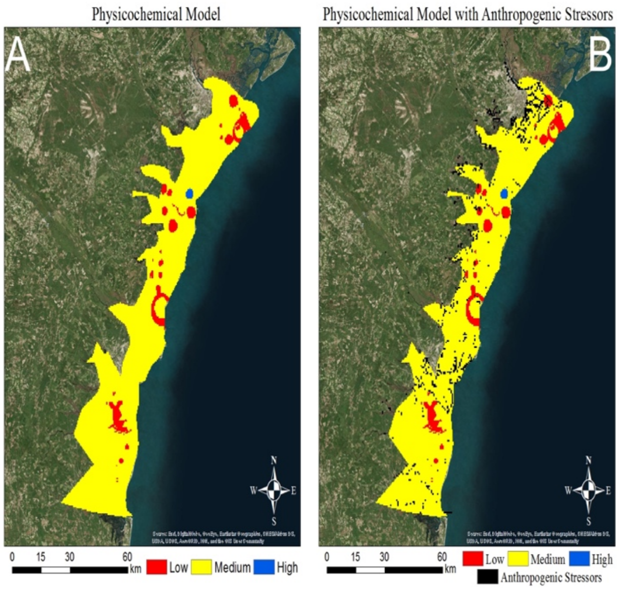

Figure 4. (A) Physicochemical model based on the summation of the water temperature, salinity, and pH data. (B) Physicochemical model with anthropogenic stressors excluded.

Although, these reefs are restricted to the shallow areas along the banks of the rivers. It is possible that the salinity ranges along the banks are less saline than the middle of the rivers where this data was collected (Sanders, Mangelsdorf Jr., & Hampson 1965). A study attempting to answer this question would be a beneficial contribution to this model.

The CRD water quality data was used for the physicochemical model due to the wide spatial distribution of testing sites and the consistency of monitoring. We believe the consistency of the data and the spatial distribution contribute to the utility of our index. The three physicochemical parameters highlighted a wide variety of locations and show that habitat quality is highly variable by parameter. This variation is not surprising considering the dynamic nature of the Georgia coast.

The physicochemical model results were expected. Much of the coast fell into the medium habitat quality range which includes values in the accepted range for oyster survival but are not necessarily ideal for recruitment (Dekshenieks, Hofmann, and Powell 1993). It is interesting that there was only one distinct area along the entire coast that produced a high habitat quality rating. There were several low habitat quality sites throughout the coast. However, more high and low habitat quality areas were expected (Harris 1980; Manley, Power, & Walker 2008). The exclusion of habitat near anthropogenic stressors highlights important locations to avoid when considering projects in medium and high quality habitat.

Several improvements can be made to this preliminary model. First, obtaining a larger time range of data from the CRD shellfish water quality monitoring program will be beneficial. By increasing the number of years, it will be possible to include longer term variation into the index. This would produce an index that accounts for a more complete set of conditions occurring at each location. Secondly, introducing additional anthropogenic stressors into the model would areas exclude additional areas from consideration and further prioritize locations with higher potential for success. Third, incorporating proximity to pre-existing oyster reefs as spat sources could improve the utility of the index. The Georgia coast is not typically spat limited but restoration areas in other states may be spat limited (Manley, Power, & Walker 2008). Fourth, biological monitoring on pre-existing oyster reefs in each of the habitat quality ranges could be used to evaluate the index. These surveys should focus on signs of stress or lack of spat recruitment

This preliminary model may be able to assist in planning oyster reef restoration projects by identifying areas where physicochemical conditions are favorable to oyster success. Additionally, we argue that the utility in our index is that it targets more efficient management of restoration assets.

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