Article

Spatial and temporal variability in spat settlement of intertidal oyster reefs support site-specific assessments for restoration practices

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**Abstract:** As some of the most productive ecosystems in the world, the declining condition and coverage of coastal habitats consequently results in the loss of the myriad economic and ecosystem services they provide. Mitigation efforts to address these deficits have been initiated in many places worldwide. Due to variability in physical and biological characteristics across sites , increased place-based information to inform local management projects with the goals of reestablishing economic and ecological function of coastal habitats are imperative. As oysters are often used in many of these projects, particularly living shorelines, a form of natural stabilization that also provides habitat, this study quantified spatial and temporal patterns in eastern oyster spat settlement in a bar-built estuary in northeast Florida, USA that is host to a robust population of intertidal oyster reefs. Understanding how spat settlement varies in a dynamic region with two inlets and a short residence time is valuable for projects seeking to use this species behavior of gregarious settlement in establishing functional oyster reefs as part of restoration projects. There is variability in spat settlement in different regions of the area in which higher counts often coincide to watersheds with higher residence times and years with \_\_\_\_\_ conditions.

**Keywords:** restoration, spat, oysters, water quality

1. Introduction

Coastal ecosystems are some of the most productive in the world providing numerous ecosystem services such as carbon sequestration, improvement of water quality, erosion control, and recreation (Brown et al., 2006; Barbier, 2007). Recognizing their value and aesthetic, these ecosystems are subject to constant human activity which has ultimately led to the steady deterioration in many habitats of these systems (Barbier, 2007). Worldwide, there has been an estimated loss of 35% of mangroves, 30% of coral reefs, 29% of seagrasses, 50% of salt marshes, and 85% of oyster reefs (Brown et al., 2006; Valiela et al., 2001; Orth et al., 2006; MEA 2006; FAO 2007; Beck et al., 2011). With the loss of these coastal habitats, the critical ecosystem services and economic value of those services decline as well, such has been seen in the number of viable (non-collapsed) fisheries (-33%), provision of nursery habitats (-69%), and filtering and detoxification services (-63%) (Worm et al. 2006). The mitigation of anthropogenic effects is of significant need in these systems.

As such, efforts in the restoration and enhancement of these habitats have increased with their decline in ecosystem and economic function. The use of organic materials in these projects has additional benefits beyond mere construction material. Living shorelines, a form of natural stabilization using organic materials, have been found to improve water quality, cease or reverse coastal erosion, and serve as critical habitats for plants, fishes, and invertebrates (Scyphers et al., 2011; Whalen et al., 2011; Kreeger and Padeletti, 2013). One common type of living shoreline is a shellfish-based living shoreline (Rupasinghe et al., 2024) which has the advantages of adapting with a changing climate; such as oyster reefs being able to grow at the pace of sea level rise (Rodriguez et al., 2014) and being able to self-repair after a destructive event (Gittman et al., 2014). Oysters have been established as “ecosystem engineers'' (Dame 1996) due to the fact that they can maintain, modify, and form habitats. As such, oysters are an ideal target material in mitigation projects in coastal ecosystems with oyster reef habitats as often a primary or secondary goal of these installations is utilizing their gregarious settlement behavior to continue to form and strengthen these installations over time.

Abundant and common to the southeastern United States, the eastern oyster *Crassostrea virginica* (Gmelin, 1791) forms three-dimensional reefs which enhance secondary and tertiary productivity within estuaries as juvenile fish and crustaceans recruit to and utilize these reefs as foraging grounds and refuge (Breitburg 1999; Coen and Luckenbach 2000; Harding and Mann 2003; Grabowski et al., 2005; Tolley and Volety 2005; Boudreaux et al. 2006; Rodney and Paynter 2006). Additionally, oyster reefs provide other types of ecosystem services such as water filtration, prevention of coastal erosion, boat wake mitigation, and carbon sequestration (Volety et al., 2014).

Eastern oysters are non-incubatory oysters, meaning they release gametes into the water column and fertilization occurs outside of the organism (Galstoff, 1964). Eastern oyster larvae remain in the planktonic stage for about 2-3 weeks before settling on a suitable substrate, from which they are known as “spat”. Many abiotic and biotic factors influence the timing and extent of spawning to the recruitment and survival of juvenile oysters. Understanding the effect of these factors across this spectrum has great importance in the timing and success of many restoration projects with the goals of forming a functional oyster habitat as part of their design. Spawning response has been shown to be variable by the sex of the oyster (Galstoff, 1964), temperatures and salinity of the water (Ingle, 1952; Butler, 1949), and availability of food for adult oysters (Hofmann et al., 1992; Dekshenieks, 1993). Temperature, salinity, and circulation patterns are amongst the most notable factors to affect oyster larvae (Nelson and Perkins, 1931). Temperature and food supply have been found to affect the length of larval periods (Underwood and Fairweather, 1989). To a lesser degree, turbidity of the water also can affect larval growth as well as settlement. Larvae tend to settle on the underside of objects or in crevices, presumably to avoid light and silt, but have been found on the surfaces of objects in higher turbidity conditions (Kennedy, 1980; Nelson, 1953). Lastly, field studies have shown that settlement and recruitment of oyster larvae often has high inter-regional and interannual variability (Michener and Kenny, 1991; Horse et al., 1972; Lee, 1979; Sauod et al., 2000; Kim et al., 2010). Understanding spat settlement patterns within regions with restoration goals is valuable to planning for this installation and success.

The goal of this study was to quantify spatial and temporal variability in a dynamic bar-built estuary in northeast Florida, USA, that is host to a robust population of intertidal oyster reefs and to establish patterns of spat settlement to inform oyster-based restoration and enhancement projects. Understanding the variability of spat settlement in previous field studies in the southeast, as well as differences in oyster densities in the region (Dix 2009; Marcum et al., 2018), it was expected that there would be spatial variability amongst study sites. Therefore, potential drivers of this variability were also examined to provide further insight into differing characteristics amongst regions and years.

2. Materials and Methods

2.1. Study Sites

The Guana-Tolomato-Matanzas (GTM) estuary is a bar-built estuary with enclosed lagoons “rivers” (the Guana, Tolomato, and Matanzas) that trifurcate at the St. Augustine Inlet (Figure 1). This inlet is one of two in the system, and it is maintained and stabilized with a jetty by the United States Army Corps of Engineers to a depth of 5-m. The other, the Matanzas Inlet, is an unstructured inlet just north of Marineland, Florida, USA. The estuary is well-flushed with a short residence time of approximately 12.6 days (Phlips et al. 2004; Sheng et al. 2008; Gray et al. 2021) and is well-mixed, meaning vertical stratification in salinity is homogenous. The GTM estuary hosts exceptionally intact and robust populations of eastern oysters that filter approximately 60% of the estuary’s volume within a single residence time (Gray et al. 2021). There is also a functional oyster fishery (commercial and recreational) in several regions.

**Map

Description automatically generated**

**Figure 1.** Map of the Guana Tolomato Matanzas National Estuarine Research Reserve boundary (black line, bottom inset: red), spat collector locations (black dots), water quality monitoring stations (black triangles, not included in insets), and regions: Tolomato River (turquoise), Guana River (pink), Salt Run (yellow), St. Augustine (red), and Fort Matanzas (blue). Water quality stations are from the System-Wide Monitoring Program and are Pine Island (“PIWQ”), San Sebastian (“SSWQ”), and Fort Matanzas (“FMWQ”).

The GTM National Estuarine Research Reserve (GTMNERR) initiated a monitoring program for local oysters in 2014 in which a regional approach was adopted based on perceived differences in water quality, food availability, hydrodynamics, harvesting, and management (Marcum et al. 2018). Regions were created based on the major waterways along the Atlantic Intracoastal Waterway (ICW): Tolomato River, Guana River, Salt Run and Matanzas River. A similar approach was used in this study; however, the Matanzas River region was further subdivided into St. Augustine (the northern portion of the river) and Fort Matanzas (the remaining portion of the river to the south) due to hydrological differences associated with the two inlets (Figure 1). Additionally, the GTMNERR maintains continuous long-term water quality monitoring stations within the GTM estuary as part of the System-Wide Monitoring Program (SWMP) of the National Estuarine Research Reserves (NERRS). Data from these stations was used to examine relationships in spat settlement with environmental conditions. All SWMP data are publicly available through the NERRS Centralized Data Management Office (CDMO) webpage (NERRS 2022).

2.2. Data Collection

2.2.1. Spat Tree Deployment

A stratified random sample of three reefs in each region of interest (except for the Tolomato River) were selected to deploy spat collectors. The Tolomato River region had two spat collectors deployed at either end of an oyster enhancement area known as Wright’s Landing, where 275 m2 of oyster reefs (28 individual reefs) were created from bagged shell in 2012 and 2013, and one across from the site on a natural reef. In June 2016 and June 2020, one additional spat collector was deployed in the St. Augustine and Tolomato regions, respectively.

Patterns in spat settlement were monitored using the hanging shell method. Samples were collected using T-shaped structures (trees) made from PVC, with shell “stringers” suspended from each side of the crossbar (Figure; Arnold et al. 2008, Haven and Fritz 1985, Parker 2015, Volety and Savarese 2001, Wilson et al. 2005). Each stringer was composed of six cleaned eastern oyster shells that were between 5 to 10 cm in shell height. Holes were drilled through the shells, and they were strung onto galvanized wire oriented with the inner concave surface facing down. Prior to deployment, shells were cleaned by soaking in bleach water for 48 hours followed by removal of all fouling organisms by scrubbing with a wire brush. After bleaching, the shells were then soaked for at least 24 hours in freshwater as a rinse.

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**Figure 2.** An example of a spat tree deployed on an oyster reef.

Trees were inserted into the reef at the apparent densest portion of live oyster on the reef and situated so that the shells were at the approximate height of the surrounding live oysters. All regions had trees deployed starting in February 2015 except for the Tolomato River, which was initiated in September 2015. These trees were left to soak for approximately one month upon which they were collected. During collection, any fouling organisms were removed from the tree, and new stringers were deployed. The retrieved stringers were labeled and stored in a -4°C freezer until processed. Efforts were made for the stringers to remain deployed for one month, however due to logistics, there was some variation in how long they were left in the field before collection. Trees were deployed for approximately 30 days on average with a range in the project of 21-43 days. Hurricane Matthew affected the study area in October 2016 and spat trees were unable to be collected, resulting in missing data from September and October of that year.

2.2.2. Shell Processing and Counting

Shells were assigned numerical IDs based on their position on each stringer, with the topmost shell designated number one and the bottommost number six. The top and bottom shells (one and six, respectively) were discarded and shells two through five were evaluated for spat abundance.

In early years of the monitoring, spat were counted using the naked eye or a magnifying glass on both sides of the shells (interior and exterior). A small-scale comparison study determined that spat abundance was significantly higher using a dissection microscope and on the inner surface (bottom of the shell) only. Beginning in December 2017, all processing was done under microscope on the inner surface of the shells. A linear regression equation based on the comparison was developed to correct the non-microscope data for analysis:

|  |  |
| --- | --- |
| S = 1.4658*b* + 1.0378 | (1) |

where S was the adjusted number of spat counted and *b* was the observed number of spat counted on the bottom of the shell by naked eye. The average number of spat per shell was calculated for each tree deployed within each region each month. These values were then rounded to convert the number of spat to integers.

2.3 Water Quality

Water quality data used in this study were downloaded from the CDMO for the Pine Island (PIWQ), San Sebastian (SSWQ), and Fort Matanzas (FMWQ) stations for the continuous water quality information (Figure 1)(DATA CITATION). These stations were equipped with YSI EXO2 data sondes mounted to wooden pilings and deployed approximately one meter from the bottom. The sondes measure a variety of parameters every 15-minutes including water temperature (°C), salinity (psu), and turbidity (NTU). Discrete water samples were collected in duplicate at these same stations once a month for chlorophyll *a* (chl-*a,* µg/L*)* on a morning ebb tide from as close to the sonde depth as possible. Samples were filtered in the field, placed on ice in the dark and shipped overnight to the Florida Department of Environmental Protection’s Central Laboratory in Tallahassee, FL. Chl-*a* was extracted from frozen filters within 28 days and analyzed using spectrophotometry (SM10200H; citation).

The data had undergone the quality assurance and quality checks of the CDMO methods (CDMO MANUAL CITATION) and data flagged as “rejected” and “suspect” were removed from the dataset for analysis. The duplicate chl-*a* samples from each station were averaged by month. All water quality data was then further aggregated inside and outside the defined spat settlement periods for descriptive statistics.

2.4. Data Analysis

All data analysis and visualizations were created using R programming language (R Core Team, 2023). Several helpful import, filtering, and aggregating functions from the SWMPr package in R were used for the compilation of the water quality data (Beck 2016).

Since oyster count data has been shown to fit a negative binomial distribution, a generalized linear regression model with a negative binomial distribution was used to compare for differences in spat settlement per region and across years (Moore et al. 2020). Spat counts per shell were assumed to be related to the amount of time they were left “soaking” during deployment; therefore, to control for this the number of soak days was included as an effort offset (log link function; Zuur et al. 2013). This causes the models to predict the rate measured as count per deployment, while maintaining the dependent variable as an integer of counts. The dependent variable was the average spat count for each collector rounded as an integer. The independent variables (main effects) were both categorical and these were region and year. Multiple models were fitted to the data: Model 0 was the intercept only, Model 1 included region, Model 2 included region and the year, Model 3 included the interaction of region and year, and Model 4 included just year (Table 1).

Comparisons were made between models with different combinations of independent variables using Akaike’s Information Criterion (AICc). The lowest AICc value represents the best fit of the models tested (Table 1; Burnham and Anderson 2002). Models were fit to the data using the glmmTMB package (Brooks et al. 2017), assessed with the performance package (Lüdecke) and predicted values (marginal means) and pairwise comparisons with Tukey adjustments were made from the best fit model using the emmeans (Lenth 2024) package in R. All data visualizations and summaries were performed using tidyverse functions in ggplot2 (Wickham 2016) and dplyr (Wickham).

3. Results

3.1. Spatial and Temporal Variability in Spat Settlement

Average annual spat settlement increased from the start of the project in 2015, reaching the highest regional averages in 2020 in all regions except Guana River (GR) (Figure 3). Peak settlement shifted from early summer in 2015 to late summer in 2017, which continued for the remainder of the monitoring. Timing of minor peaks appeared to forecast peak abundance: reefs with minor peaks that occurred later in the spring had higher spat abundance both during the fall peak as well as annually (Figure 3).

Chart, histogram

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**Figure 3.** Monthly mean spat per shell for each region from 2015-2020 with panels broken up in two-year segments: Tolomato River (TR, green); Guana River (GR, pink); Saint Augustine (SA; orange); Salt Run (SR, yellow); and Fort Matanzas (FM, blue). Note the difference between the scales of the y-axis and missing data in the fall of 2016 due to Hurricane Matthew (October 2016).

Five different models were fit to the spat per shell data (Table 1; Appendix). The best fitting model included terms for region and year. The dispersion ratio from the negative binomial distribution was 1.527 (*p* < 0.001), suggesting overdispersion. No significant interaction was found between year and regions; however, autocorrelation in the residuals was detected in the model (Kolmogorov-Smirnov test: *p* = 0.034, Durbin-Watson test: *p* < 0.001). Since the model results found significant patterns in region and year, comparisons were made using estimated marginal means and Tukey’s post-hoc tests to identify where those differences were found in the levels of each factor.

**Table 1.** Model selection table for generalized linear model of eastern oyster spat count data standardized by days left out in field for settlement on deployed collectors (“trees”) in different regions within the Guana Tolomato Matanzas estuary, Florida, USA. The predicted response is the average spat per shell per collector (spat\_count). Akaike’s Information Criterion (AICc) and the AICc difference (ΔAICc) are provided to inform comparisons of the model statistical fit to the data (*k* is the number of parameters) and are ranked from lowest AICc to highest in the table. Region and year are both categorical variables in which region describes the location of the collection and year is the year of study. Soak\_days is the amount of time in days that spat trees were deployed.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Model** |  |  | ***k*** | **AICc** | Δ**AICc** | **AICc weight** |
| Model 2: spat\_count ~ region + year + offset[log(soak\_days)] |  |  | 11 | 6484.63 | 0.00 | 1 |
| Model 3: spat\_count ~ region + year + region:year +  offset[log(soak\_days)] |  |  | 31 | 6504.43 | 19.81 | 0 |
| Model 4: spat\_count ~ year + offset[log(soak\_days)] |  |  | 7 | 6559.31 | 74.69 | 0 |
| Model 1: spat\_count ~ region + offset[log(soak\_days)] |  |  | 6 | 6613.63 | 129.00 | 0 |
| Model 0: spat\_count ~ offset[log(soak\_days)] |  |  | 2 | 6688.57 | 203.94 | 0 |

Tolomato River (TR) had the greatest mean spat per shell (logarithmic-transformed estimated marginal mean [EMM]: 3.33, confidence interval [CI] = 3.09 – 3.58; untransformed mean: 43.11) and Fort Matanzas (FM) the least (EMM: 1.91, CI = 1.68 – 2.14; 9.97) (Figure 4A; Table 2). Variability in counts was also much higher in the TR region than all other regions and overall counts were significantly higher than all other regions. There was no difference found between GR (EMM: 2.77, CI = 2.54 – 3.00) and St. Augustine (SA; EMM: 2.63, CI = 2.39 – 2.86) and these regions were much higher than Salt Run (SR; EMM: 2.08, CI = 1.83 – 2.34) and FM (Figure 4A).

Spat settlement increased in all regions across the study period (Figure 2; Figure 4B). Between the first year (2015; EMM: 1.57, CI = 1.25 – 1.88) to the final year of the study (2020; 3.56, CI = 3.31 – 3.80), there was a 77.58% increase in the mean number of spat per shell. Both 2015 and 2016 (EMM: 1.73, CI = 1.44 – 2.01) were significantly lower than all the other years. The following two years 2017 (EMM: 2.41; CI = 2.15 – 2.66) and 2018 (EMM: 2.79; CI = 2.55 – 3.04) were higher, though not different from one another. Lastly, the final two years of the study, 2019 (EMM: 3.22; CI = 2.98 – 3.46) and 2020, had the highest counts per shell (Table 2).

**Table 2.** Estimated marginal means (EMM) for mean spat per shell in the five regions and between 2015-2020 in the Guana Tolomato Matanzas estuary. Results for regions are averaged over the levels of year and for years are averaged over the levels of region. All values are given on the log (not the response) scale. SE = standard error, CI = confidence level of 0.95.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **EMM** | **SE** | **CI** |
| Region | Tolomato River (TR) | 3.33 | 0.13 | 3.09 – 3.58 |
| Guana River (GR) | 2.77 | 0.12 | 2.54 – 3.00 |
| St. Augustine (SA) | 2.63 | 0.12 | 2.39 – 2.86 |
| Salt Run (SR) | 2.08 | 0.13 | 1.83 – 2.34 |
| Fort Matanzas (FM) | 1.91 | 0.12 | 1.68 – 2.14 |
|  | 2015 | 1.57 | 0.16 | 1.25 – 1.88 |
|  | 2016 | 1.73 | 0.14 | 1.44 – 2.01 |
|  | 2017 | 2.41 | 0.13 | 2.15 – 2.66 |
|  | 2018 | 2.79 | 0.13 | 2.55 – 3.04 |
| Year | 2019 | 3.22 | 0.13 | 2.98 – 3.46 |
|  | 2020 | 3.56 | 0.12 | 3.31 – 3.80 |

**Chart, scatter chart

Description automatically generated**

**Figure 4.** Mean spat per shell in the five regions (panel A) of the Guana Tolomato Matanzas estuary: Tolomato River (TR, green); Guana River (GR, pink); Saint Augustine (SA; orange); Salt Run (SR, yellow); and Fort Matanzas (FM, blue). Mean spat per shell in all regions for each year (panel B) of the study. Group means (raw and untransformed) are represented by the large black dots with the mean value presented in a call-out box next to the dot in each plot. Each point in the plots represents a sampled collector per month between 2015-2020. Letters indicate Tukey’s post-hoc test results and years/regions with differing letters are significant to each other (*p* < 0.001).



3.2. Patterns in Annual Spat Settlement

Overall, spat settlement appears to occur in all regions in the GTM estuary between April and November each year (Figure 5). Typically, a minor peak in settlement occurs in the mid-late spring and a much larger and regular peak occurs after the summer in September. All regions have more spat settlement between April – November than outside of this period (Table 3). For most regions, there is over 180% difference between spat settlement inside and outside of the settlement period. FM has the smallest difference between 313 (se = 110) average spat per year inside the settlement period and 26 (se = 14) outside the settlement period, but this difference is still well over 100%.

**Chart, line chart

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**Figure 5.** Monthly mean spat per shell with settlement period indicated as the thick dashed line between April and October for the five regions in the Guana Tolomato Matanzas estuary: Tolomato River (TR, green); Guana River (GR, pink); Saint Augustine (SA; orange); Salt Run (SR, yellow); and Fort Matanzas (FM, blue) based on data collected from 2015-2020.

**Table 3.** Summary information for spat settlement per shell in regions in the Guana Tolomato Matanzas estuary inside the annual settlement period (April – October) and outside of the settlement period (January – March and November – Dec). Metrics include average total settlement per shell per year (standard error) and average settlement per shell (standard error).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | ***Avg. Total Settlement***  ***Per Shell Per Year*** | | ***Avg Settlement***  ***Per Shell*** | |
| **Region** | **Inside** | **Outside** | **Inside** | **Outside** |
| Tolomato River (TR) | 1234 (466) | 38 (13) | 75 (10) | 3 (1) |
| Guana River (GR) | 571 (18) | 18 (5) | 29 (4) | 2 **(**1) |
| St. Augustine (SA) | 677 (249) | 27 (11) | 35 (6) | 2 **(**1) |
| Salt Run (SR) | 305 (100) | 16 (5) | 19 (4) | 2 **(**1) |
| Fort Matanzas (FM) | 313 (110) | 26 (14) | 17 (4) | 2 **(**1) |

3.3. Drivers of Variability

Water quality varied across the six years of this study at all stations (Figure 6). Average monthly water temperatures were relatively consistent from year to year and among stations except for a cold snap in the winter between 2017 and 2018 (Figure 6A). There are differences in the salinity, turbidity, and chl-*a* regimes at all the sites with Pine Island (PI) having lower salinity and higher turbidity and chl-*a* than San Sebastian (SS) and Fort Matanzas (FM). There was a large peak in chl-*a* at FM in the spring of 2018 (Figure 6D). Turbidity appeared to be much higher between 2017-2019 (Figure 6C).

**Chart, histogram

Description automatically generated

**Figure 6.** Monthly average water quality parameters at the Guana Tolomato Matanzas National Estuarine Research Reserve System-Wide Monitoring Program stations: Pine Island (PI, green), San Sebastian (SS, orange), and Fort Matanzas (FM, blue). Temperature (A), Salinity (B), and Turbidity (C) are all aggregated from 15-minute data from continuous instruments deployed at each site. Chlorophyll *a* (D) is collected monthly in duplicate at each station as a grab sample.

Examining monthly aggregated data revealed some distinctive patterns in water quality across the years and stations; however, further investigation into monthly minimum salinities (Figure 7A) and maximum turbidity (Figure 7B) revealed more distinctive patterns between years. Salinity at the stations that typically averaged more saline (FM and SS) fell well below 30 PSU in the early fall of 2017 and remained relatively low until 2020. There was also a sharp decrease in salinity at the FM station in the late summer of 2019. Monthly turbidity spikes were observed in the fall of 2016 and 2017, and in the early spring of 2020.

Water quality conditions were different within the settlement period (April – October) compared outside (January – March, November – December) the period (Table 4). Temperature, salinity, and chl-*a* are higher inside the period than outside. Turbidity patterns appear to show no differences associated with the months of spat settlement.

Graphical user interface, chart, histogram

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**Figure 7.** Water quality parameters at the Guana Tolomato Matanzas National Estuarine Research Reserve System-Wide Monitoring Program stations: Pine Island (PI, green), San Sebastian (SS, orange), and Fort Matanzas (FM, blue). (A) Monthly minimum salinity (PSU) and (B) monthly maximum turbidity (NTU) between 2015-2020.

**Table 4.** Summary statistics of water quality parameters collected from the Guana Tolomato Matanzas National Estuarine Research Reserve System-Wide Monitoring Program stations inside the spat settlement period (April – October) and outside of the settlement period (January – March, November – December). Temperature (Temp., Celsius), salinity (Sal., PSU), and turbidity (Turb., NTU) are calculated from 15-minute data from data sondes continuously deployed at each station. Chlorophyll *a* (Chl-*a*, µg/L) is collected monthly in duplicate at each station. All data is from the period of the study: January 2015 – December 2020. SE = standard error.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Station** |  | ***Inside Settlement Period*** | | | | ***Outside Settlement Period*** | | | |
|  | **Temp** | **Sal** | **Turb** | **Chl-*a*** | **Temp** | **Sal** | **Turb** | **Chl-*a*** |
| Pine Island | Mean  SE | 27.88  0.01 | 26.34  0.02 | 15.58  0.02 | 6.07  0.01 | 18.62  0.01 | 24.57  0.02 | 9.25  0.01 | 3.88  0.01 |
| Min | 18.1 | 2.5 | 2.0 | 1.75 | 7.1 | 7.6 | 0.0 | 1.7 |
| Max | 33.7 | 38.9 | 357.0 | 13.5 | 28.7 | 35.7 | 96.0 | 9.15 |
| San Sebastian | Mean  SE | 27.04  0.01 | 33.5  0.01 | 11.76  0.02 | 5.19  0.01 | 18.45  0.01 | 32.17  0.01 | 9.71  0.02 | 3.81  0.01 |
| Min | 17.1 | 15.4 | 0.0 | 2.0 | 8.6 | 21.4 | 1.0 | 1.9 |
| Max | 33.2 | 38 | 265.0 | 10.5 | 27.5 | 36.5 | 301.0 | 7.15 |
| Fort Matanzas | Mean  SE | 26.85  0.01 | 33.84  0.01 | 9.71  0.02 | 4.88  0.01 | 18.57  0.01 | 32.87  0.01 | 7.37  0.01 | 2.66  0.004 |
| Min | 17.5 | 1.7 | 1.0 | 1.55 | 8.2 | 16.3 | 1.0 | 0.93 |
| Max | 32.9 | 38.0 | 178.0 | 15.5 | 28.1 | 36.3 | 174.0 | 6.6 |

4. Discussion

*4.1 Spatial Variability in Spat Settlement*

Within the GTM estuary, there were differences between regions in levels of spat settlement. The Tolomato River (TR) region consistently yielded the highest spat averages throughout the duration of this study. Unlike trees deployed in the other regions of the project, two of the three spat trees in the TR were deployed along an enhanced site. The TR region was established in September 2015 (seven months later than the other regions) and was initially one natural reef (TR1). In 2016, two more trees were installed (TR2 and TR3) along Wright’s Landing. Wright’s Landing was the site of an enhancement project by the GTMNERR and Northeast Florida Aquatic Preserves to establish a living shoreline of constructed oyster reefs and coconut fibre coir logs along the Guana Peninsula in 2013 to mitigate shoreline loss. Though the fibre coir logs failed within a few months following their installation (Dunnigan Thesis 2015), the constructed reefs, which were made of plastic mesh bags filled with oyster shells and stacked in 25-ft long segments along the shoreline, remained intact for a few years before some of the bags began to break open and release the oyster cultch across the sediment. It was along this shoreline in which the two trees were deployed to track spat settlement in 2015.

The settlement success was often higher in the trees deployed along the constructed reefs, compared to the tree across the river in a natural oyster reef, leading to the high variation in the region over the course of the study. A fourth tree was deployed in 2020 within the natural reef area to further understand the counts between the enhanced site and natural reefs across the river, but the counts from this tree were left out of the analysis due to the short timeframe of its deployment. While the higher spat average at Wright’s Landing reefs could be indicative of artificial reef success, it is also possible that open exposure to water, lack of competing structure in the area, and possible entrapment by a sandbar influenced settlement rates. In addition to the installed artificial reef, this shoreline is also protected by a sandbar that protrudes out into the river along the length of the installation. This well-documented sandbar provides a protected anchorage basin along the river and is the first place north of the St. Augustine Inlet to provide anchorage adjacent to arable land. Thus, this site has a long history of use dating back to the British Period as a plantation and a Second Spanish Period Minorcan farmstead and evidence of these settlements still exist and are continued to be studied (Meide et al. 2010). It is unclear whether the presence of this sandbar, and its influence on the adjacent shoreline, was taken into consideration in the planning of the enhancement project at Wright’s Landing. Small-scale hydrodynamics, such as the entrapment by a sandbar, in oyster recruitment have been highlighted by several studies (Sussan and Charpentier, 2024; Fuchs and Reidenbach, 2013; Whitman and Reidenbach, 2012). The Wright’s Landing reefs, artificial and natural, were near the boating channel, which could contain oyster larvae that were transported from the shallower tributaries during the outflowing ebb tides (Sussan and Charpentier, 2024).

The differential flushing, tidal, stratification, and wind regimes across regions make comparisons across field studies difficult, while emphasizing the importance of place-based studies to establish patterns. and Differences in spat settlement between two tributaries in the Chesapeake Bay in Maryland, USA were found to likely be the result of different circulation patterns that exposed the less productive tributary to fewer larvae, no matter the source of their larvae (Kennedy and Krantz 1982). In addition to the TR region, the Saint Augustine (SA) region also had high rates of spat settlement. The high rates of spat settlement in this region could be attributed to the high residence time of this area. Recent hydrodynamic studies of the GTM estuary characterized the regional residence times and the watershed in in which the trees were deployed for the SA region had residence times exceeding 30 days (Gray et al. 2022). The TR region was also found to have a high residence, at 16.1 days. The high residence times of these regions could allow for the oyster larva that are suspended in the water column to settle in the region before being carried away by currents to a different region or out to the sea.

The region with the lowest spat settlement in this study was Fort Matanzas (FM) which had

* Trees were deployed north and south of the 206 bridge. This area has been found to be a tidal node between the inlets
* Florida Statutes have estuarine nutrient regions defined north and south of this bridge
* Watersheds were used north and south of the 206 bridge in Gray et al. 2022.
* Tidal nodes can fluctuate

A potential factor that could play into the regional patterns of spat settlement is the presence of oyster harvesting regions. The Wright’s Landing and SA regions exist in oyster harvesting prohibited areas. The presence of more sexually mature oysters than compared to harvestable regions, like the Fort Matanzas (FM) and Salt Run (SR) regions, could possibly play a role in the higher spat counts for the SA and TR regions.

*4.2 Temporal Changes in Spat Settlement*

Overall, spat settlement increased over the course of the study and peak settlement shifted from early to late summer. Reefs that experienced a minor peak in May as opposed to April tended to yield more spat per shell both annually and during the primary settlement period.

Kenny et al 1988 found timing and duration of settlement in *C. virginica* in North Inlet, SC to be similar each year, but spatfall within years varied significantly (over a 5-year study period). There were also no consistent relationships between settlement intensity, late-stage larval density in the water column, water temperature, or salinity.

In general, oysters in more southern portions of their range exhibit longer spawning periods than their more northern counterparts. Peak settlement in September has been found in North Carolina (Ortega and Sutherland 1992) and North Inlet, South Carolina (Kenny et al. 1990). The length of the settlement period in this study (April – November) was similarly to other studies in similar latitudes along the southeastern United States and Gulf of Mexico (Kenny et al. 1990; Moore and Trent 1971; Ingle 1951; Butler 1965). The peak settlement was variable by location in both the Gulf of Mexico studies.

*4.3 Climate Impacts to Water Quality and Spat Settlement*

* Several climatic events occurred during the six years of this study.
  + There were tropical cyclones in 2016 (Hurricane Matthew), 2017 (Hurricane Irma), and 2019 (Hurricane Dorian).
    - Hurricane Irma, in particular, caused persistent changes in water quality conditions well into the summer of 2018. *\*pull in information from Schaefer et al. 2022 and Brown et al. 2023\**
      * Peak in chl-*a* biomass at FM in spring 2018 (following Irma…upland draining, etc.)
    - There was a [cold snap in 2018](https://www.clickorlando.com/weather/2018/01/04/orlando-wakes-up-to-coldest-temps-in-nearly-4-years/)
      * *What do we know about oyster larvae and spawning in the area? Raabe and Gilg 2020 examined zooplankton patterns…. Anything from Todd and Jose Nunez??*

*4.4 Other Considerations*

Spat settlement often higher on natural reefs than on collectors in adjacent habitats ([Newell et al. 2000](https://link.springer.com/article/10.1007/s002270050726)). “Although spat settlement has been found to be lower on collection devices than natural reefs in the area…”

5. Conclusions

Understanding the spatial and temporal patterns of spat settlement can help inform management to allow for informed restoration practices to maximize results. Spat in the Guana-Tolomato-Matanzas estuary settle between April and November with peak settlements typically occurring in September. Further investigation into timing of annual settlement and spring and late fall water quality conditions can provide insight into the role of climate-related events into oyster spawning and settlement patterns in an estuary along the eastern coast of the United States. Results of this study illustrate region- and year-specific variability in oyster settlement patterns and underscore the importance of local monitoring for oyster resource management, restoration, and research.

**Supplementary Materials:** The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

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**Data Availability Statement:** We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section “MDPI Research Data Policies” at https://www.mdpi.com/ethics.

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**Appendix A**

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

**Table 2.** This is a table. Tables should be placed in the main text near to the first time they are cited.

|  |  |  |  |
| --- | --- | --- | --- |
| **Title 1** |  | **Title 2** | **Title 3** |
| entry 1 |  | data | data |
| entry 2 |  | data | data 1 |

1 Tables may have a footer.

**Table 1.** Model results for the best-fitting generalized linear model (Table # in text) of oyster spat counts per shell on collectors deployed in five regions in the Guana Tolomato Matanzas estuary from 2015-2020 where spat count per shell = region + year + offset[log(soak time)]. Parameter estimates are on a log scale. Dispersion parameter 0.374.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Estimate** | **SE** | ***z*-value** | **Pr(>*z*)** |
| Intercept | -1.06 | 0.21 | -5.06 | < 0.001 |
| Guana River (GR) | -0.56 | 0.17 | -3.24 | < 0.01 |
| Saint Augustine (SA) | -0.71 | 0.17 | -4.12 | < 0.001 |
| Salt Run (SR) | -1.25 | 0.18 | -6.96 | < 0.001 |
| Fort Matanzas (FM) | -1.42 | 0.17 | -8.25 | < 0.001 |
| 2016 | 0.16 | 0.22 | 0.74 | 0.46 |
| 2017 | 0.84 | 0.21 | 4.07 | < 0.001 |
| 2018 | 1.23 | 0.21 | 5.95 | < 0.001 |
| 2019 | 1.65 | 0.2 | 8.12 | < 0.001 |
| 2020 | 1.99 | 0.21 | 9.70 | < 0.001 |

**Table 2a.** Pairwise comparisons of mean spat per shell between sampled regions in the Guana Tolomato Matanzas estuary: Tolomato River (TR), Guana River (GR), Saint Augustine (SA), Salt Run (SR), and Fort Matanzas (FM). Results are averaged over the level of year and given on the log (not the response) scale. Tukey method for post-hoc tests. SE = standard error.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Contrast** | **Estimate** | **SE** | ***z*-ratio** | ***p*-value** |
| TR – GR | 0.56 | 0.17 | 3.24 | 0.0105 |
| TR – SA | 0.71 | 0.17 | 4.12 | 0.0004 |
| TR – SR | 1.25 | 0.18 | 6.96 | < 0.0001 |
| TR – FM | 1.43 | 0.17 | 8.25 | < 0.0001 |
| GR – SA | 0.14 | 0.17 | 0.85 | 0.916 |
| GR – SR | 0.69 | 0.18 | 3.90 | 0.0009 |
| GR – FM | 0.86 | 0.17 | 5.12 | < 0.0001 |
| SA – SR | 0.54 | 0.18 | 3.12 | 0.0162 |
| SA – FM | 0.72 | 0.17 | 4.30 | 0.0002 |
| SR – FM | 0.18 | 0.18 | 0.998 | 0.8565 |

**Table 2b.** Pairwise comparisons of mean spat per shell among sampling years in the Guana Tolomato Matanzas estuary. Results are averaged over the levels of region and given on the log (not the response) scale. Tukey method for post-hoc tests. SE = standard error.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Estimate** | **SE** | ***z*-value** | **Pr(>*z*)** |
| 2015 – 2016 | -0.16 | 0.22 | -0.74 | 0.9775 |
| 2015 – 2017 | -0.84 | 0.21 | -4.07 | 0.0007 |
| 2015 – 2018 | -1.23 | 0.21 | -5.95 | < 0.0001 |
| 2015 – 2019 | -1.65 | 0.20 | -8.12 | < 0.0001 |
| 2015 – 2020 | -1.99 | 0.21 | -9.70 | < 0.0001 |
| 2016 – 2017 | -0.68 | 0.19 | -3.52 | 0.0057 |
| 2016 – 2018 | -1.07 | 0.19 | -5.55 | < 0.0001 |
| 2016 – 2019 | -1.49 | 0.19 | -7.88 | < 0.0001 |
| 2016 - 2020 | -1.83 | 0.19 | -9.59 | < 0.0001 |
| 2017 – 2018 | -0.38 | 0.18 | -2.12 | 0.2745 |
| 2017 - 2019 | -0.81 | 0.18 | -4.53 | 0.0001 |
| 2017 – 2020 | -1.15 | 0.18 | -6.39 | < 0.0001 |
| 2018 - 2019 | -0.42 | 0.18 | -2.40 | 0.1572 |
| 2018 - 2020 | -0.76 | 0.18 | -4.31 | 0.0002 |
| 2019 - 2020 | -0.34 | 0.17 | -1.96 | 0.3635 |

**Appendix B**

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled starting with “A”—e.g., Figure A1, Figure A2, etc.

References

References must be numbered in order of appearance in the text (including citations in tables and legends) and listed individually at the end of the manuscript. We recommend preparing the references with a bibliography software package, such as EndNote, ReferenceManager or Zotero to avoid typing mistakes and duplicated references. Include the digital object identifier (DOI) for all references where available.

Citations and references in the Supplementary Materials are permitted provided that they also appear in the reference list here.

In the text, reference numbers should be placed in square brackets [ ] and placed before the punctuation; for example [1], [1–3] or [1,3]. For embedded citations in the text with pagination, use both parentheses and brackets to indicate the reference number and page numbers; for example [5] (p. 10), or [6] (pp. 101–105).

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EXAMPLES

1. Author 1, A.B.; Author 2, C.D. Title of the article. *Abbreviated Journal Name* **Year**, *Volume*, page range.
2. Author 1, A.; Author 2, B. Title of the chapter. In *Book Title*, 2nd ed.; Editor 1, A., Editor 2, B., Eds.; Publisher: Publisher Location, Country, 2007; Volume 3, pp. 154–196.
3. Author 1, A.; Author 2, B. *Book Title*, 3rd ed.; Publisher: Publisher Location, Country, 2008; pp. 154–196.
4. Author 1, A.B.; Author 2, C. Title of Unpublished Work. *Abbreviated Journal Name* year, *phrase indicating stage of publication (submitted; accepted; in press)*.
5. Author 1, A.B. (University, City, State, Country); Author 2, C. (Institute, City, State, Country). Personal communication, 2012.
6. Author 1, A.B.; Author 2, C.D.; Author 3, E.F. Title of Presentation. In Proceedings of the Name of the Conference, Location of Conference, Country, Date of Conference (Day Month Year).
7. Author 1, A.B. Title of Thesis. Level of Thesis, Degree-Granting University, Location of University, Date of Completion.
8. Title of Site. Available online: URL (accessed on Day Month Year).

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