Assessing resistance to recovery in oyster populations – inferences from inadequate monitoring programs

Cognitive dissonance

*Introduction* - Eastern oyster populations in the northern Gulf of Mexico are depressed from historic levels for reasons that are poorly understood. Since 2010, the states of Florida, Alabama, Mississippi, Louisiana, and Texas have all declared state or federal level oyster fishery disasters citing reasons including prolonged drought, intense rain events, or freshwater releases from water management structures (refs) and Florida has engaged in litigation at the US Supreme Court level over oyster population collapse in Apalachicola Bay (ref). Several of these states have implemented fishery closures in response to depressed status of oyster stocks (i.e., Mobile Bay in Alabama, Apalachicola in Florida) but only one of these stocks (Mobile Bay) has reopened to harvest with Apalachicola scheduled to re-open in 2025. Oyster populations in the Gulf of Mexico were also damaged by the sinking of the *Deepwater Horizon* and subsequent oil spill (Deepwater Horizon Natural Resources Damage Assessment Trustees, 2016) which created substantial funding opportunities (more than $199M US) for oyster restoration in the Gulf of Mexico exceeding the annual value of oyster landings (Pine et al. 2022).

Many proposed, ongoing, recent, and historical oyster restoration efforts focus on the addition of various materials for oyster spat (larvae) to settle and grow. Adding this material to substrate is an effort to promote a positive oyster shell budget (harvest removes shell stock, Pine et al. 2015). This is done by providing material from outside of the system of management interest to replace degraded (but natively created), displaced (from culling during harvest) or removed (from harvest) cultch to mimic natural oyster cultch; a complex matrix of living and dead material where oyster larvae settle and grow. These restoration efforts are an attempt to shift oyster reefs from an observed low but resilient state to a more desired productive state Pine et al. 2022) through restoration actions.

We used opportunistic sampling from ongoing and recently completed efforts to shift oyster populations from undesired to desired states through restoration and fishery closure projects in estuaries in the northern Gulf of Mexico. Many of the large restoration programs that are currently funding these efforts are long-term (10-year) projects, but information as learning is needed over shorter time scales to inform other proposed restoration and management projects in similar systems. This is an issue of both temporal and spatial scale (Pine et al. 2022). To facilitate learning under an adaptive management framework as programmatically adopted by these funders, these restoration efforts should be assessed in-progress, and if necessary, corrective changes made to improve the likelihood of the restoration objective of shifting the oyster population from an undesired low-level, to a more desired level. This desired state can vary by location, and type of oyster bar (intertidal vs. subtidal), and management goals. But in general, the desired expectation motivating these restoration efforts are to provide and promote both ecosystem services (ref) and create opportunities for oyster harvest through fishery recovery.

*Site description* – We assessed trends in oyster populations in three estuaries in the Florida panhandle that currently have ongoing or recently completed oyster restoration projects. Pensacola Bay (F1) in northwest Florida (Santa Rosa and Escambia counties) is the fourth largest estuary in Florida with a surface area of approximately 126,000 total acres. Reported oyster landings and trips for Pensacola Bay in recent decades have suggested XYZ (F2) since the current mandatory TRIP ticket program was implemented in 1986. The East Bay (F1) arm of St. Andrew Bay, near Panama City (Okaloosa and Walton Counties) is one region of St. Andrew Bay with a total surface area of approximately XYZ acres. Reported oyster landings and trips for Easy Bay are not available, but for the counties comprising St. Andrew Bay oyster trips and landings in recent decades have ??? (F2). Apalachicola Bay is a large estuary in Franklin County which historically supported the largest oyster fishery in Florida before collapsing in fall of 2012 (Pine et al. 2015) and was closed to commercial harvest in December 2020 through December 2025.

*Management actions* – Cultch material was deposited in each bay in phases by individual state management agencies (Florida Department of Environmental Protection, DEP; Florida Fish and Wildlife Conservation Commission, FWC; Florida Department of Agriculture and Consumer Services, FDACS) as part of three different projects funded to the State of Florida with funds made available following the *Deepwater Horizon* oil spill. In Pensacola Bay approximately 20,103 cubic yards of limerock aggregate were distributed at 17 different sites at an approximate density of 228 cubic yards per acre (FDACS 2016a) during September and October 2016. In St. Andrews Bay approximately 17,000 cubic yards of crushed granite was distributed on nine different oyster reefs at a density of about 200 cubic yards per acre (FDACS 2016b) in June 2016. In Apalachicola Bay two different restoration projects with similar objectives and methodologies occurred during this time. In the first (FDEP), approximately 95,500 cubic yards of limerock aggregate was deployed as part of an FDEP project on fourteen different oyster reef sites. Average density of cultch material was 300 cubic yards per acre. The second (FWC) deployed 9600 cubic yards of shell material in sites 2-acres in size at densities of 100, 200, 300, or 400 cubic yards per acre. Across all studies the actual area and density of cultch material deployed varied due to construction challenges and storm events that occurred during the study period.

*Methods*

Reef construction – Reef construction methods across studies were similar and were designed to minimize costs and maximize amount of material deployed. Sites were selected for cultch placement based on local knowledge of historic or extant reef locations. Cultch material was deployed on site from barges by washing material from barge deck using high pressure hoses at a prescribed density.

Field collections – Similar methods were followed for all projects to estimate live oyster counts and mass of cultch material based on methods used in Florida since the 1980’s (FWC 2021 <https://myfwc.com/media/27745/oimmp-v2-ch11.pdf>) where divers haphazardly place ¼-m2 quadrats at selected sites and remove all oysters and cultch material to a “wrist deep” depth and place material in bags. Once bags are returned to the vessel, they are either processed on site or returned to the lab where counts of live and dead oysters, measurements of shell height, weight of cultch material, and other metrics depending on study were recorded.

Data Analyses – We followed methods for analyzing oyster count data described in Moore et al. (2020). Briefly, we summed counts of live oysters at each restoration site and period into three size classes, spat (<26-mm shell height), sublegal (26-75-mm shell height), and legal (>76-mm shell height) and assessed the distribution the count data followed by examining the ratio between the variation of the counts and the mean count per site. We then used generalized linear models (GLMs; Bolker et al. 2009) with a negative binomial distribution to assess how oyster counts (dependent variable) vary over period (a time variable of equal length used to combine sampling months into winter [November-April] or summer [May-October]) and we used site as a random effect. We assumed that the total oyster counts per site would be related to the number of quadrats collected at each site, so we included the number of quadrats as an offset of effort (log link function; Zuur et al. 2009, 2013). By using effort as an offset in this way we change the model from modeling counts, to modeling a rate measured as the count/quadrat as the response variable. Because the quadrats were the same size across study, the area sampled only changed as a function of the number of quadrats. Using counts and account for effort, as opposed to converting the counts to CPUE based on density sampled has two main advantages in our experience (1) maintains the response as an integer allowing the use of a negative binomial distribution (which we have observed oyster count data follow; Moore et al. 2020) and (2) fitted values and confidence intervals do not contain negative values (Zuur et al. 2009). We fit models to the data that included time (period), location (as a random effect), and then used the best fitting model (informed by AIC value and visual assessments of model fit to data) to predict oyster counts by period and location using the glmm.TMB (Brooks et al. 2017) and ggeffects packages (Lüdecke 2018) in R (R Core Team 2021). Data and all code used for analyses is available from the following Git repository ABCDEF.

*Results*

*Oyster spat counts across Apalachicola, Pensacola, and St. Andrews Bays across reefs restored with rock cultch*

Based on AIC, GLM models that include Bay (Apalachicola, Pensacola, St. Andrews) and Period (Bay + Period) or an interaction term between Bay\*Period with site within the Bay as a random effect and the number of quadrats as an offset were not different (delta AIC = 0.3). Because our interest is in how counts of oyster spat change over time (as a restoration effort to shift the system from an undesired to desired state) we were most interested in the Bay + Period model. For this model, Period was not significant (beta = 0.003, SE beta = 0.05, p=0.95) suggesting across all three Bays oyster spat counts did not change significantly over time. However, the beta value is positive, and a back transformed value (*exp*0.003) suggests a change of about 1 live oyster spat per period. Examining each Bay across Period suggests a significant change in Apalachicola live spat over time (beta = 1.83, SE beta = 0.47, p <0.001) and in St. Andrews Bay (beta = 3.85 SE beta = 0.90, p < 0.001) but not for Pensacola Bay (beta = 2.38, SE beta = 0.82, p = 0.11). Predicted mean live oyster spat counts (95% CI) for the last period of the time series (period 14) from a single ¼-m2 are Apalachicola = 18.5 (9.5 - 35.8), Pensacola = 25.5 (12.9 - 50.4), and St. Andrews = 134.4 (63.63 - 283.72) which are declines from the predicted values for each Bay at the beginning of the time series (Figure X, predicted with data).

Fitting the same Bay + Period model to counts of sub-legal oyster counts model results were similar with a nonsignificant change over Period in counts of live sub-legal oysters across Period (beta = -0.04, SE = 0.06, P=0.48) across all Bays. For Apalachicola Bay, counts of sub-legal oysters were also not significant (beta = 0.38, SE = 0.59, p = 0.52) but the beta coefficients were significant for Pensacola (beta = 2.41, SE = 1.05, p < 0.001) and St. Andrews bays (beta = 3.11, SE = 1.15, p < 0.001). Predicted mean live oyster sublegal counts (95% CI) for the last period of the time series (period 14) from a single ¼-m2 quadrat are Apalachicola = 2.67 (1.2 – 6.0), Pensacola = 12.8 (5.8 - 26.4), and St. Andrews = 23.2 (8.9 - 60.6) which are declines from the predicted values for all bays at the beginning of the time series (Figure X, predicted with data).

The Bay + Period model fit to counts of legal oysters were similar with a nonsignificant change over Period in counts of live sub-legal oysters across Period (beta = -0.07, SE = 0.07, P=0.31) across all Bays. For Apalachicola Bay, counts of sub-legal oysters were significant (beta = -1.37, SE = 0.61, p = 0.02) and beta coefficients for Pensacola (beta = -2.3, SE = 1.06, p = 0.06) and St. Andrews bays (beta = -0.09, SE = 1.14, p < 0.001). Predicted mean live oyster sublegal counts (95% CI) for the last period of the time series (period 14) from a single ¼-m2 are less than 1 legal adult oyster for all three bays.

##now go into other R code for detailed Apalachicola analyses

# Predicted counts of Sum\_spat

# Bay = Apalachicola

Period | Predicted | 95% CI

-----------------------------------

3 | 26.04 | [14.97, 45.31]

5 | 24.47 | [15.93, 37.58]

6 | 23.71 | [16.16, 34.81]

7 | 22.99 | [16.10, 32.81]

10 | 20.93 | [13.99, 31.32]

14 | 18.48 | [ 9.54, 35.80]

# Bay = Pensacola

Period | Predicted | 95% CI

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3 | 35.95 | [19.83, 65.18]

5 | 33.78 | [20.96, 54.44]

6 | 32.74 | [21.20, 50.57]

7 | 31.74 | [21.10, 47.73]

10 | 28.90 | [18.55, 45.02]

14 | 25.51 | [12.91, 50.42]

# Bay = St. Andrews

Period | Predicted | 95% CI

------------------------------------

3 | 189.35 | [91.00, 394.03]

5 | 177.90 | [94.92, 333.44]

6 | 172.44 | [95.61, 311.02]

7 | 167.15 | [95.16, 293.59]

10 | 152.22 | [86.21, 268.76]

14 | 134.37 | [63.63, 283.72]

# Predicted counts of Sum\_sublegal

# Bay = Apalachicola

Period | Predicted | 95% CI

----------------------------------

3 | 8.76 | [4.48, 17.13]

5 | 7.06 | [4.17, 11.95]

6 | 6.34 | [3.94, 10.19]

7 | 5.69 | [3.64, 8.88]

10 | 4.11 | [2.48, 6.81]

14 | 2.67 | [1.19, 5.99]

# Bay = Pensacola

Period | Predicted | 95% CI

-----------------------------------

3 | 41.94 | [19.67, 89.42]

5 | 33.79 | [18.31, 62.35]

6 | 30.33 | [17.36, 52.98]

7 | 27.22 | [16.18, 45.78]

10 | 19.68 | [11.51, 33.65]

14 | 12.77 | [ 5.75, 28.36]

# Bay = St. Andrews

Period | Predicted | 95% CI

------------------------------------

3 | 76.24 | [32.13, 180.94]

5 | 61.42 | [28.89, 130.57]

6 | 55.13 | [26.91, 112.96]

7 | 49.48 | [24.69, 99.20]

10 | 35.78 | [17.27, 74.13]

14 | 23.22 | [ 8.91, 60.57]

# Bay = Apalachicola

Period | Predicted | 95% CI

---------------------------------

3 | 0.55 | [0.24, 1.29]

5 | 0.48 | [0.25, 0.93]

6 | 0.44 | [0.24, 0.81]

7 | 0.41 | [0.23, 0.73]

10 | 0.33 | [0.17, 0.64]

14 | 0.25 | [0.08, 0.72]

# Bay = Pensacola

Period | Predicted | 95% CI

---------------------------------

3 | 0.23 | [0.08, 0.64]

5 | 0.20 | [0.08, 0.46]

6 | 0.18 | [0.08, 0.40]

7 | 0.17 | [0.08, 0.35]

10 | 0.14 | [0.07, 0.28]

14 | 0.10 | [0.04, 0.29]

# Bay = St. Andrews

Period | Predicted | 95% CI

---------------------------------

3 | 2.00 | [0.67, 5.99]

5 | 1.73 | [0.67, 4.49]

6 | 1.61 | [0.65, 3.98]

7 | 1.49 | [0.62, 3.61]

10 | 1.20 | [0.47, 3.05]

14 | 0.89 | [0.26, 3.10]

#ok walk through the 3 bays R code, which I think is just the DEP projects

#then go through the quadrat summary code which is just Apalach in detail with all of the projects.