Habitat Suitability Analyses for the Eastern Oyster, *Crassostrea virginica*, in the Pontchartrain Basin Estuary, Southeast Louisiana, in 2019

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**Cover Graphic:**
LPBF Hydrocoast map at the zenith of freshwater extent in June 2019, following the unprecedented double-openings of the Bonnet Carré spillway in February and May of 2019.

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Executive Summary

The Pontchartrain Conservancy’s (LPBF) prior annual suitability analyses (2013 to 2018) of the eastern oyster, *Crassostrea virginica*, demonstrated that closure of the Mississippi River Gulf Outlet (MRGO) in 2009 caused a baseline shift in surface water salinity within much of the Pontchartrain Basin, and has generally shifted oyster habitat back to the pre-MRGO reef trends. However in late 2018 and 2019, these conditions were challenged by the unprecedented flooding of the Mississippi and Pearl Rivers that required two openings of the Bonnet Carré spillway, from February 27 to April 11, and from May 10 to July 27, introducing exceptionally large volumes of freshwater entering into Mississippi Sound and the Biloxi Marsh. The Bonnet Carré spillway openings released a total of over 1.3*10^{12} cubic feet of river water into Lake Pontchartrain (~6 X the volume of the lake) destined to move eastward into Mississippi Sound. The Pearl River flooded several times early in 2019, discharging directly into Mississippi Sound. The result of all the combined discharges was the freshening (< 2 ppt) of Western Mississippi Sound, and most of the region north and east of the MRGO reaching to the very western edge of Chandeleur Sound. This report analyzes the effects on oyster suitability by the 2019 freshwater event by using monitoring data presented on LPBF’s bi-weekly Hydrocoast maps.

From 2013 to 2017, LPBF evaluated annual oyster suitability in Pontchartrain Basin using two HSI models: the Chatry Optimal Oyster Salinity Model (COOS) from Chatry et al. (1983) and the Soniat Optimal Oyster Salinity (SOOS) derived from the Eastern Oyster Habitat Suitability Index Model (Soniat 2012). Our application of these models focuses on salinity alone and does not use other variables, such as presence of hard bottom. The Modified Eastern Oyster Habitat Suitability Index Model (Denapolis 2018) is critical for analysis of changes to the suitability of oyster habitat in response to events that may influence salinity (e.g. floods, droughts, alterations to river flow, diversions etc.). For 2018, this model with input for the primary source (Dr. Tom Soniat) was used in the previous analysis to modify the HSI methodologies as “MSOOS” and “MCOOS”. The updated version of the SOOS method (MSOOS) was added to the analysis for 2018 and again for 2019 in substitution of the SOOS method to incorporate the synergistic effects of temperature and salinity, and to more comprehensively account for the effects of predation, disease, and freshwater inundations, by placing limitations on the maximum salinity of the V_{3} minimum salinity suitability index. Changes were also made to the COOS classification system (now MCOOS) to improve biological relevancy of the classes. This report provides the results of LPBF’s analysis of suitability for 2019, and a comparison of the 2018 and 2019 HSI model results using the improved MSOOS and MCOOS HSI models.

In 2019, the HSI models defined some areas north and south of the MRGO as favorable for oysters (Class 1 or 2). However, the size of suitable areas (north and south of the MRGO) were considerably smaller, and the location shifted gulfward for both analyses compared to 2018. Comprehensive results from 2013-2019 still indicate that the open-water areal extent of favorable oyster conditions was larger north of the MRGO as opposed to the area south of the MRGO. Also influencing this pattern of suitability were the effects of increased Mississippi River discharge, and the flood duration down-river at Fort St. Philip and other leakage points that freshened Breton Sound. As a result of the unprecedented freshwater inflows in 2019, the change in salinity forced suitable area for oysters to be smaller and shifted gulfward.

**The Breton Sound Sub-basin in 2019 (south of MRGO):**
- The MCOOS analysis categorized about 1% (19 km², 4,660 acres) of Breton Sound Sub-basin as favorable for oysters, and this area was confined to Breton Sound near the MRGO.
- The MSOOS analysis did not categorize any of Breton Sound Sub-basin as favorable for oysters.
• Using the MCOOS analysis, there was a 3% decrease in the areal extent from 2018 by -56 km² or -13,873 acres of favorable oyster conditions, and using the MSOOS analysis, there was a -13% decrease by -280 km², or -69,108 acres.

**The Biloxi Marsh Sub-basin in 2019 (north of MRGO):**

• The MCOOS analysis categorized over 5% (195 km², 48,218 acres) as favorable for oysters, and this region was located near the MRGO.

• The MSOOS analysis resulted in categorization of 23% (838 km², 207,169 acres) as suitable for oysters, located along the eastern-most fringe of Biloxi Marsh and a few miles into western Chandeleur Sound.

• Using the MCOOS analysis, there was an 8% decrease in areal extent from 2018 by -278 km², or -68,675 acres; and using the MSOOS analysis, there was -37% decrease by -1,388 km², or -342,898 acres.

In all of LPBF’s annual oyster analyses (2013 to 2019), MSOOS has always selected more saline areas as favorable conditions (Class 1 or 2) with an overall mean of 16.58 ppt; whereas MCOOS analyses had an overall mean of 13.23 ppt. This significant difference (25%) may be explained because MSOOS emphasizes the optimum higher salinity conditions for spawning (>17ppt); whereas, MCOOS emphasizes the density of surviving seed oysters, which can be recruited up-estuary with greater density in salinity below 15 ppt due to lack of disease and predation, and may survive with commercial density in salinity as low as 5 ppt. Each of the HSI model’s re-occurrence maps from 2013-2019, when compared to indications of actual oyster productivity such as fleet activity, indicate that both models are useful. However, further work is needed to clarify the exact biological aspects that each model may be revealing, and determine if they are truly complementary or actually have some conflicting results.

The volume of freshwater discharge in 2019 was an extraordinary event, and not surprisingly, it resulted in impacts on living marine resources. Significant oyster mortality occurred in areas of the Biloxi Marsh which our prior documentation demonstrated to be viable habitat for oysters. The 2019 freshwater event was significantly driven by the double-opening of the Bonnet Carré Spillway and Pearl River floods. With changes to the Mississippi River watershed due to increased precipitation, we can expect more spillway openings, but it is not likely to be double-openings every year and 2019 may prove to be an uncommon type event.

One silver lining in 2019 is that the region between Bayou la Loutre and the MRGO, seems to have been unscathed by oyster mortality during the 2019 freshwater event. The regional hydrology insulated this area from freshwater and severe salinity reduction in 2019. The resulting MSOOS HSI here was Class 3 (“marginal”), but was apparently sufficient to have little mortality. This area now has new relevance as a region that can survive extreme freshwater events, and allow mature oysters there to function as brood reef stock to help rebuild other areas impacted by mortality or overharvesting. With the addition of hard bottom, there may be similar potential for brood reefs in the eastern-most fringes of the Biloxi Marsh.

Since 2006, LPBF has identified the Biloxi Marsh as a component of the ten “Pontchartrain Coastal Lines of Defense”, and has promoted oyster propagation as a primary goal of restoration in the Biloxi Marsh. In 2006, LPBF successfully partnered with St. Bernard Parish and others for closure of the MRGO in 2009. Subsequently LPBF proposed oyster restoration in the Biloxi Marsh in the Coastal Master Plan (2007 through 2017). In 2019 LPBF partnered with LDWF, and built four reefs, of which three may be successful brood reefs to support oysters in the Biloxi Marsh. LPBF has proposed to the LaTIG that non-harvestable “brood reef corridors” be identified and developed along the multi-year salinity gradient so that there is likely always to be some surviving brood stocks despite extreme high or low salinity events, such as in 2019. In addition, LPBF has proposed for the 2023 Coastal Master Plan, a project to narrow
Three Mile Pass to reduce salinity fluctuations within the region. However, most significantly, we believe the oyster suitability analyses conducted since 2013, may guide public and private oyster management for the benefit of commercial fishers and the larger public who will benefit from a healthy Biloxi Marsh.

Introduction
The Mississippi River Delta comprises a series of historic and currently developing delta lobes created by Mississippi River sediment. The delta is subsiding as a result of various natural processes and anthropogenic causes such as sediment loading, compaction (Tornqvist et al. 2008), and sea level rise. A reduction in sediment transported by the river, as a result of upstream damming and cessation of overbank flow due to the construction of levees along the Mississippi River, has restricted natural delta processes that would otherwise naturally counteract the effects of subsidence. Storm events and anthropogenic activities like the introduction of non-native species and the construction of oil and gas infrastructure, further exacerbate the loss of coastal wetlands, which provide various ecosystem services (such as storm buffer, nurseries, and shoreline stabilization).

The Mississippi River Gulf Outlet (MRGO) caused massive saltwater intrusion, and had a profound effect on oyster habitat, which shifted significantly up-estuary while open. The Central Wetlands which had been largely swamp and fresh marsh, was subject to mesohaline conditions, and as a consequence there is documentation of old oysters that were growing on cypress knees and cypress stumps there. This represents a near complete collapse of the estuary while the MRGO was open. The closure in 2009, has largely reversed the salinity effects, and from 2013 to 2018, we found the oyster suitability and oyster fleet activity to be located in the Biloxi Marsh region, which is precisely where the habitat existed prior to the MRGO.

Stopping the saltwater intrusion and restoring natural deltaic processes and conditions is critical to reducing the loss of Louisiana’s wetlands. In 2009, two closure structures were constructed in the Mississippi River Gulf Outlet (MRGO) which have reduced saltwater intrusion and shifted baseline conditions to those that support pre-MRGO biomes such as swamps in many areas within the coastal zone (Henkel et al. 2017). Large-scale sediment and freshwater diversions of the Mississippi River are currently in development to restore and maintain wetlands along the Louisiana coastline (CPRA 2017). Significant effort has been placed into predicting and assessing the relationship between these restoration projects, and commercial and recreational fishery species in Louisiana, as these projects are expected to alter water quality from their most recent regimes (de Mutsert & Cowan 2012, Soniat 2012, Wang et al. 2017). The eastern oyster, *Crassostrea virginica*, is an economically and ecologically important species that shares an intrinsic relationship with freshwater inflow due to its immobility and distinct environmental requirements throughout its various life stages. Thus, determination of how freshwater flows may affect optimal locations for oyster growth in coastal Louisiana is valuable information for managers.

Eastern Oyster
Due to its economic and ecological importance, the eastern oyster is one of several key species considered in Louisiana’s 2017 Comprehensive Master Plan for a Sustainable Coast (CMP) (CPRA 2017). Louisiana has consistently produced over a third of annual eastern oyster landings in the U.S. for the past 3 decades (NMFS landings). In addition to supporting a fishery, oyster reefs provide a variety of ecosystem services such as water filtration (Nelson et al. 2004), nitrogen regulation (Piehler & Smyth 2011, Beseres Pollack et al. 2013, Hoellein et al. 2015), habitat provision (Shervette et al. 2011), and shoreline protection.
Coastal Louisiana lost 5,197 km² of coastal wetlands from 1932-2016 (USGS & Department of the Interior 2017), which makes the protection of coastal wetlands by oyster reefs of particular importance to the region. Natural oyster reefs comprise multiple generations of oysters, with younger oysters settling on previously established living or deceased individuals on the reef. This results in a vertical accretion of oyster reef into the water column, which reduces wave energy and protects adjacent habitats such as marshes (Ridge et al. 2016) and seagrass (Sharma et al. 2016).

Natural oyster reefs have been in decline worldwide due to a variety of natural and anthropogenic disturbances such as oil spills (Powers et al. 2017) and overfishing (Rothschild et al. 1994, Kirby 2004, Wilberg et al. 2011). Common fishing practices reduce the vertical relief and hard structure necessary for oyster survival and larval recruitment (Lenihan & Peterson 1998, Lenihan 1999). Replacing or creating three-dimensional structure via the addition of cultch and/or other substrates, addresses this limitation, and these artificial habitats assume the provision of ecosystem services over time such as, shoreline protection (Meyer et al. 1997, Soniat et al. 2004, Piazza et al. 2005) and habitat provision for various faunal communities (Dillon et al. 2015). Constructing oyster reefs is costly (~$500,000/hectare in 2011, Blomberg et al. 2018), and substantial planning must be made to ensure environmental conditions (e.g. salinity, temperature, and dissolved oxygen) will result in restoration success and long-term reef sustainability.

The influence of salinity on oyster populations is dictated by its interactions with other factors, including temperature, dissolved oxygen, and oyster size class. Oyster growth, reproduction, and larval setting share a positive relationship with increasing salinity (La Peyre et al. 2016, Priester 2016, Lowe et al. 2017), however warmer temperatures and higher salinity make oyster populations susceptible to the pathogens *Perkinsus marinus* (Dermo) and *Haplosporidium nelsoni* (MSX) (Craig et al. 1989, Chu & La Peyre 1993, Petes et al. 2012). The latter has not been found in the Gulf of Mexico (Ford et al. 2011), but Dermo is known to have caused mass oyster mortalities in the region (Ray 1996) by the inhibition of reproductive processes (Dittman et al. 2001), and growth (Menzel & Hopkins 1955). Increased freshwater inflows reduced Dermo infection intensities (La Peyre et al. 2009, Beseres et al. 2011, La Peyre et al. 2013), and the presence of oyster predators that thrive in more saline waters, such as oyster drills (Gunter 1953, Gunter 1955, La Peyre et al. 2009, Beseres Pollack et al. 2011, La Peyre et al. 2013).

However, prolonged freshwater floods can be detrimental to oyster populations, particularly when coupled with warmer temperatures. Oysters close their valves in response to salinity below 5 ppt, which restricts feeding and aerobic respiration, and persistent low salinity conditions limit growth, fecundity, and survival (Butler 1949, Loosanoff 1953, Casas et al. 2018). Responses to low salinity are exacerbated by warm temperatures, which govern the timing of oyster reproduction, and can therefore have significant effects on recruitment of new individuals into a population (Loosanoff & Davis 1952, Hayes & Menzel 1981). Additionally, the increased metabolic rate of larger sized oysters makes them more susceptible to mortality arising from prolonged exposure to salinity below 5 ppt and warm temperatures than larval and juvenile oysters (Loosanoff 1953, Dame 1972, La Peyre et al. 2013, Rybovich et al. 2016).

Lowe et al. (2017) studied the relationship between spat, seed, and market-sized oyster growth and mortality of oysters for region-specific populations along coastal Louisiana. The study used long-term dredge monitoring data from the Louisiana Department of Fisheries and Wildlife (LDWF), which generally included data from 2000-2014. While the influence of temperature and salinity varied across basins and age class, the authors found that the combined optimal range of temperature and salinity for spat, seed, and market-sized oyster growth was 20.0-26.3 °C and 10.7-16.1 ppt. Additionally, the authors also found that salinity greater than 15 ppt and water temperatures greater than 30 °C caused higher market-sized oyster mortality than salinity below 5 ppt and the same high water temperatures.
Identifying areas with salinity conducive to oyster recruitment, growth, and survival is critical to ensuring the long-term sustainability of constructed oyster reefs. Chatry et al. (1983) derived an optimal salinity regime for seed oyster production (oysters in the size range of 26-75 mm) by studying the relationship between seed oyster abundance and salinity on Louisiana public seed grounds in Breton Sound (within the current study area) for a period of 10 years (1971-1981; Figure 1). The authors’ optimal salinity regime was used to inform operations management of the Caernarvon Freshwater Diversion (CFD). The authors also provided a linear relationship through which the deviation of a region’s observed salinity from the optimum salinity regime can be used to estimate its production of seed oysters in the following year.

Figure 1 Observed optimal annual salinity regime for seed oyster production of the following year on Breton public seed grounds from 1971-1980 (Chatry et al. 1983). This graph illustrates the Chatry Optimum Salinity Regime (OSR) referenced throughout the current study.

Habitat suitability models classify the suitability of the environment for a biological population. The Eastern Oyster Habitat Suitability Index Model (Soniat 2012), includes environmental variables (culch availability, mean annual salinity, minimum salinity, and spawning season salinity) to classify the suitability of conditions for self-sustaining oyster populations. The model is a revision of a previous eastern oyster model (Soniat & Brody 1988), which itself was a modification of the Cake 1983 model designed for use by U.S. Fish and Wildlife Services. Soniat’s 2012 model is currently used by many state, federal and non-governmental organizations to assess environmental suitability for current and future Louisiana coastal restoration projects in the CMP (CPRA 2017). Modifications to Soniat’s 2012 model were made in 2018 (Denapolis 2018) that additionally address the effects of temperature, predators and disease on environmental suitability for the eastern oyster in southern Louisiana.

Specialized models have also been developed to inform restoration efforts. Starke et al. (2011) created a model to identify areas of the Hudson River and New York Harbor suitable for reef restoration. The
model focused on substrate suitability, reef height, and salinity. Pollack et al. (2012) developed a model to identify suitable areas for restoration in a south Texas estuary. The model incorporates depth as a determinant of reef construction feasibility with shallow areas (<1 m) being unnavigable to barges, which are commonly used in transporting and deploying substrate in large oyster restoration projects (Pollack et al. 2012). La Peyre et al. (2015) developed a model to identify coastal shorelines most at risk to erosion to maximize the provision of shoreline protection services provided by restored oyster reefs.

In light of efforts to divert Mississippi River flows and sediment to combat wetland loss, and given the current status of local oyster reefs and their role in protecting coastal wetlands, oyster restoration will play a critical role in providing coastal protection, contributing to oyster resiliency, and augmenting natural and commercial oyster stocks. Planning to ensure the successful restoration of oyster populations and ecosystem services is critical. The purpose of this study is to guide ongoing restoration efforts at the Pontchartrain Conservancy, assess the relationship between oysters and the dynamic estuarine environment over multiple years, and inform the various entities that rely on oysters as a fishery and provider of ecosystem services. This report is a continuation of oyster habitat suitability analyses in the Pontchartrain Basin from 2013-2018 by the Pontchartrain Conservancy (Preau et al. 2016, Hopkins & Lopez 2017, De Santiago & Lopez 2018, Denapolis & Lopez 2019).

Pontchartrain Conservancy Efforts to Enhance Oyster Habitat

Pontchartrain Coastal Lines of Defense System (PCLODS)

The Coastal Sustainability Department at LPBF devised PCLODS in 2009 to outline ten priority projects from the Comprehensive Habitat Management Plan (LPBF 2006) that may provide flood protection to Pontchartrain Basin residents (LPBF PCLODS). This approach has been adopted by the US Army Corps of Engineers and the State’s Master Plan. The restoration project locations span from the northwestern shores of Lake Pontchartrain to the Chandeleur Islands, and aim to restore and maintain land bridges and ridges, marshes, and barrier islands and reefs. The Biloxi Marsh is an important layer of protection from storm surge and wave action (USACE 2009). Reef development is encouraged as a focal point of PCLODS to connect land bridges and marsh (LPBF PCLODS).

LDWF / LPBF Biloxi Marsh Artificial Reefs

Lake Pontchartrain Basin Foundation (Pontchartrain Conservancy) and the Louisiana Department of Wildlife and Fisheries entered a cooperative agreement to create four artificial reefs located in St. Bernard Parish, in or around Biloxi Marsh, in 2019. Each reef is composed of a combination of natural bottom, cultch material (limestone and oyster shell), and structured hard material (reef balls) in an effort to enhance the biological benefits of the reef, complexity of the reef structure, and to promote oyster survival (Lenihan 1999, Soniat et al. 2004, Piazza et al. 2005). Three of the reefs (Cabbage, Grand Banks, and Karako) were built on or near historic oyster grounds dating back to pre-MRGO surveys from 1910 (Figure 2) in areas with recurring conditions that are suitable for oyster cultivation (Figures 2 & 3), and LDWF added live diploid oysters set on crushed shell at the West Karako reef site in summer of 2020. The fourth reef (Lake Borgne) was constructed upon an abandoned shell pad in an area where exploratory dives produced sparse living oysters. None of the reefs fall in sampled areas of high (>50%) recurring hypoxia (Figures 3 & 4), and all reef locations were chosen to avoid observed high commercial oyster and shrimp fleet densities.

Additionally, in April of 2020 LPBF submitted comments (Supplementary Document 1) to the U.S Fish and Wildlife Service regarding the Louisiana TIG Draft Restoration Plan/ Environmental Assessment #5: Enhancing Oyster Recovery Using
Brood Reefs proposed installation of brood reefs in Biloxi Marsh (NOAA). Based upon multiple years of data collection and analysis, LPBF recommended several locations in Biloxi Marsh for brood reef corridors (Supplementary Document 1). This collection of reefs would enhance habitat connectivity, and could function as a source to promote spat set on neighboring reefs.

Figure 2. Historic Map showing new LDWF / LPBF artificial reefs and conditions prior to the creation of the Mississippi River Gulf Outlet (MRGO).
Figure 3 Map showing LDWF / LPBF artificial reefs, recurring hypoxia and MCOOS favorable areas.

Figure 4 Map showing LDWF / LPBF artificial reefs, recurring hypoxia and MSOOS favorable areas.
Methods

Study Area

The study area encompassed roughly 19,867 km² (4,900,000 ac) and included the Pontchartrain Basin and the coastal regions from Mississippi Sound to Dauphin Island, AL (Figure 5). Oyster habitat suitability models were processed for the entire aquatic extent of the study area for 2019 for comparison to previous years, however emphasis was placed on the Biloxi Marsh and Breton Sound Sub-Basins.

Figure 3. Study area encompassing the southeast region of Lake Pontchartrain Basin, coastal areas from Mississippi Sound to Mobile Bay, AL, and extending into the Gulf of Mexico. Mississippi River Gulf Outlet (MRGO), Breton National Wildlife Refuge Department (BNWR), Louisiana Department of Health (DHH).

The Biloxi Marsh Sub-Basin includes Biloxi Marsh and Chandeleur Sound (Figure 5), encompassing the areas northeast of the MRGO, west of Breton National Wildlife Refuge (BNWR), and south of Lake Borgne and Mississippi Sound. The Pearl River, Bonnet Carré Spillway and various rivers and bayous (i.e. Amite River, Tickfaw River, Tangipahoa River) introduce freshwater into the region from the north and west. The Chandeleur Islands function as a barrier to the euhaline (30-40 ppt) waters of the Gulf of Mexico.

The Breton Sub-Basin includes Breton Sound Estuary marsh and Breton Sound and incorporates areas southwest of the MRGO, east of the Mississippi River, and is bounded on the east by Breton
National Wildlife Refuge (BNWR). The Caernarvon Freshwater Diversion is a controlled river diversion at the head of Breton Sound Estuary with a mean discharge of 3,107 cfs from 2013-2019 (USGS Caernarvon). The Bohemia Spillway is an 11.8-mile flood relief outlet designed to overflow its banks during high Mississippi River stages and has an estimated peak annual flow of 30,000 to 50,000 cfs (Lopez et al. 2013). Two distributaries, Mardi Gras Pass and Fort St. Philip, were formed by the Mississippi River’s overtopping of its banks, and introduce freshwater into lower Breton Sound Estuary.

The MRGO and its spoil bank, a hydrologic barrier which divides the two basins, is a 122 km (76 mile) long channel constructed by the U.S. Army Corps of Engineers from 1958 to 1968 to provide a shorter navigation route between the Gulf of Mexico and the Port of New Orleans. The canal was deemed an ecological disaster that diminished coastal wetlands via direct displacement (construction and subsequent erosion) and saltwater intrusion (Shaffer et al. 2009), and disrupted benthic communities by contributing to bottom water hypoxia (Poirrier et al. 2009). Two closures were constructed to prevent salt intrusion and storm surge, including a rock dam constructed at the MRGO’s intersection with the Bayou La Loutre ridge, and the Inner Harbor Navigation Canal Lake Borgne Surge Barrier both completed in 2009. While these closures reduced saltwater intrusion and bottom water hypoxia (Poirrier 2013), the affected region (Lakes Maurepas, Pontchartrain and Borgne), is still in the process of returning to pre-MRGO regimes (Henkel 2017).

Habitat Suitability Index Mapping
Oyster habitat suitability index (HSI) maps were derived using LPBF’s Hydrocoast Maps (Connor et al. 2019, LPBF Hydrocoast maps), a collection of biweekly environmental quality maps (i.e. salinity, dissolved oxygen, weather) generated from both discrete and continuous water-quality monitoring resources such as Louisiana Department of Fisheries and Wildlife (LDWF), National Oceanic and Atmospheric Administration (NOAA), Louisiana Department of Health (LDH), and Pontchartrain Conservancy sampling efforts. Surface salinity maps depict isohaline contours that are manually delineated according to discrete data points and various coastal, hydrological, and weather processes. Monthly mean salinity rasters are created by interpolating biweekly salinity contours for each respective month (January-December).

A 500m x 500m cell grid was created (Fishnet Tool) which was converted to a point file (Feature to Point Tool). Data from the monthly mean salinity rasters was then extracted to the point feature class (Extract to Multi). Model components were created using the methods of Preau et al. (2016). Spatial analyses were performed using ArcGIS 10.6 (ESRI 2017).

Modeling
Modified Chatry Optimal Oyster Salinity (MCOOS)
The Chatry OSR is a set of monthly-specific values that represent the monthly means of the observed optimal salinity regime for seed oyster production in Breton Sound seed grounds from 1971-1980 by Chatry et al. (1983) (Table 1). The absolute difference between each monthly mean salinity raster and the Chatry Optimum Salinity Regime (Chatry OSR, Table 1) was calculated (Raster Calculator Tool) for a single year. The monthly absolute differences were summed (Raster Calculator Tool), and the sum was classified into four classes according to the MCOOS values in Table 2. The resulting summed surface represents the total deviation of that year’s mean monthly surface salinity from Chatry’s OSR, where lower values are indicative of higher suitability. Although Chatry et al. (1983) found a negative
relationship between seed oyster production and deviation from the optimum salinity regime by which production could be estimated, they did not classify deviations from the Chatry OSR. The classes of the MCOOS analysis were based on Chatry et al. (1983) designation of seed oyster density of at least 20 oysters/m² as the minimum amount necessary to support commercial industry (Table 2). Chatry et al. (1983) showed that deviations ranging from 0-25 ppt from the Chatry OSR yielded >41.89 oysters/m² the following year, and therefore are categorized as Class 1. Deviations ranging from 25-33 ppt from the Chatry OSR yielded 20-41.89 oysters/m² the following year (Class 2), and Class 3 deviations (33-48 ppt) produced 0-20 oysters/m² the following year. Class 4 deviations (above 48 ppt) produced no seed oysters/m² (actually occurred at a deviation sum of 48.86 ppt). Conditions classified as Class 1 or 2 by the MCOOS analysis are considered favorable to seed oyster production in the following year, or as a representation of conditions favorable for oysters to populate at commercial densities. This methodology is referred to as the Modified Chatry Optimal Oyster Salinity (MCOOS) analysis in the current study.

Table 1. Optimal monthly mean salinity values (ppt) from Chatry et al. 1983 were used to calculate deviations and classify oyster habitat suitability from 1971-1981. These values define the Chatry Optimum Salinity Regime (OSR) referenced in this study.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
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<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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</thead>
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<tr>
<td>Salinity (PPT)</td>
<td>16.4</td>
<td>14.4</td>
<td>11.6</td>
<td>8.0</td>
<td>7.0</td>
<td>12.5</td>
<td>12.7</td>
<td>15.7</td>
<td>17</td>
<td>16.8</td>
<td>16.1</td>
<td>15.7</td>
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Table 2. Classes and defining characteristics for MSOOS and MCOOS methodologies.

<table>
<thead>
<tr>
<th>MSOOS</th>
<th>MCOOS</th>
<th>HSI Map Legend</th>
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<tbody>
<tr>
<td>MSOOS HSI Value</td>
<td>MSOOS Suitability Class Biological Description</td>
<td>MCOOS HSI Value</td>
</tr>
<tr>
<td>0.85 - 1.0</td>
<td>Highest suitability of environment for successful spawning, recruitment and survival to a commercial harvest density.</td>
<td>0 - 25</td>
</tr>
<tr>
<td>0.6 - 0.85</td>
<td>Moderate environmental suitability likely to support some spawning, moderate recruitment, and adequate survival, possibly to lighter commercial harvest density</td>
<td>25 - 33</td>
</tr>
<tr>
<td>0.3 - 0.6</td>
<td>Marginal suitability of environment indicating that spawning is unlikely, some recruitment and survival are possible but not to commercial harvest density</td>
<td>33 - 48</td>
</tr>
<tr>
<td>0 - 0.3</td>
<td>Environment generally unsuitable indicating minimal to no spawning, recruitment or survival</td>
<td>&gt; 48</td>
</tr>
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Modified Soniat Optimal Oyster Salinity (MSOOS)
The modified Soniat optimal salinity analysis (MSOOS) is based on Soniat’s 2012 Eastern Oyster Habitat Suitability Index Model and employs three of Soniat’s variables: mean spawning season salinity (V2), annual minimum salinity (V3), and historic (annual) mean salinity (V4) (Figure 6). Suitability Index (SI) values are calculated from the linear relationships shown in Denapolis (2018). The Habitat Suitability Index (HSI) value is the geometric mean of all SI values for a year, ranging from 0 to 1, with 0 being unsuitable and 1 being most suitable. If any SI value is zero, the resultant HSI value is also zero. Soniat’s
(2012) original \(V_2\) and \(V_4\) variable relationships remained unchanged, and the MSOOS methodology excluded the variables of percent land coverage \((V_5)\) and percent suitable cultch \((V_1)\) from the analysis, as incorporating the various islands, channels, and minute waterbodies would be a cumbersome task on a basin or sub-basin wide scale. The addition of cultch is unnecessary given the act of restoration will provide the hard structure required for oyster populations to develop. A bi-modal relationship using month as a proxy for temperature where April-September were defined as warm months \(V_{3w}\), and October-March were defined as cool months \(V_{3c}\) was used to calculate the minimum salinity suitability index \((V_3)\) to incorporate the synergistic effects of temperature and salinity (now Min/Max salinity), and to account for predation and disease in Louisiana’s eastern oyster populations. The relationship of low salinity in warm months was altered from the Soniat’s original (2012) \(V_3\) to reflect the increase in mortality that occurs when low salinity coincide with warmer temperatures (vs. cooler temperatures) (Denapolis 2018). The relationship of high salinity for both warm and cool months were also altered from the original \(V_3\) to reflect mortality caused by predation and disease as a function of salinity (Denapolis 2018). The minimum mean monthly surface salinity value was determined (Cell Statistics Tool) separately for warm (April – October) and cool month (November – March) groupings and the calculated SI value (Denapolis 2018), corresponding to whichever grouping had the lower mean salinity, was chosen for the final \(V_3\) (indicating the largest impact) to be used in HSI calculations. Monthly mean surface salinity rasters were used to calculate mean spawning salinity \((V_2)\) from May-September and annual mean surface salinity \((V_4)\) from January-December (Cell Statistics Tool). Suitability index (SI) values were calculated for each raster according to the adjusted relationships in Denapolis (2018), and the unweighted geometric mean of the 3 suitability index values (SIs) was calculated to return the HSI. The HSI values were assigned biologically based classes consistent with the values in Table 2.

The MSOOS analysis defined Class 1 (HSI values > .85) regions as having the highest suitability for successful spawning, recruitment and survival for an oyster population to reach a commercial harvest density (Table 2). Class 2 (HSI values 0.6-0.85) represent moderate environmental suitability that is likely to support some spawning, moderate recruitment and adequate survival for light or limited commercial harvest. Class 3 (HSI values 0.3-0.6) is defined as marginal suitability indicating that spawning may be unlikely and although some recruitment and survival are possible, it is unlikely that the population density would be able to support commercial industry. Class 4 (HSI values 0.0-0.3) is considered sub-marginal, signifying minimal to no spawning, recruitment or survival. This methodology is referred to as the Modified Soniat Optimal Oyster Salinity (MSOOS) analysis throughout the current study.
Polygon and Centroid Analysis

Polygons outlining the highest classifications of the MSOOS and MCOOS (Class 1 or 2) analyses in the Biloxi Marsh Sub-basin were created (Raster to Polygon Tool) and centroids were then calculated for polygons (Feature to Point Tool). The centroids represent the polygon centers and were calculated for each year from 2013-2019. Centroids for 2019 were compared to centroids from 2013-2018. There were no areas in Biloxi Marsh Sub-Basin in 2017 that were classified as Class 1 or 2 by the MCOOS analysis.

Hypoxia

Bottom water hypoxia (dissolved oxygen <2 mg·L⁻¹) was periodically monitored (excluding 2009) in Chandeleur Sound from 2008-2019 (10 years) and Breton Sound from 2013-2019 (6 years). Polygons were drawn around points where hypoxia was observed at least once in a given year. Polygons were then converted to rasters (Polygon to Raster Tool) and given a value of 1 across the raster’s extent. Rasters were summed (Cell Statistics Tool: processing extent was set to “Union of Inputs”) to calculate the total number of years in which hypoxia was observed in the study area. Frequency of occurrence was designated as either frequent (>50% of years sampled) or occasional (<50% of years sampled) and polygons were created to denote those areas.

Oyster Fleet Survey

LPBF conducted four aerial fleet surveys in the Pontchartrain Basin in March – August of 2019 to gather data on the areas of oyster production in the region. The location of and number of active fishing vessels was documented during flights and imported into ArcGIS (ESRI 2017). Fleet survey data
was compiled into one shapefile (Merge Tool) and divided into two shapefiles (Clip Tool), one located in public seed grounds and one outside the grounds. A density raster was created (Point Density Tool) for each group. The created rasters' grid cells measured 500 m x 500 m and the search area for each cell was set to a square measuring 5 km x 5 km. The resultant value for each cell was the number of boats per km² within it. The rasters were then clipped separately to the public seed grounds and private lease areas.

Results

Salinity
The 2019 study area presented a gradient of mean annual surface salinity, ranging from freshwater (<0.5 ppt) in the west (Lake Maurepas) to the euhaline waters of the Gulf of Mexico to the east (30-34 ppt) (Figure 7). Mean annual surface salinity in Biloxi Marsh Sub-basin ranged from 2 ppt on its Lake Borgne (western) border, to 12-14 ppt at the eastern marsh edge. Chandeleur Sound showed 14-30 ppt annual mean surface salinity. In Breton Sound Sub-basin, mean annual surface salinity increased from freshwater (<0.5 ppt) in the upper estuary, to 4 ppt at mid estuary, reaching 10-12 ppt in the lower estuary and Breton Sound. Mean annual surface salinity increased from <0.5 ppt to 4 ppt radiating westward from the Mississippi River. Figure 8 illustrates the effect of the 2019 freshwater event to the annual salinity compared to the prior six years.

Figure 5. Hydrocoast annual mean surface salinity in the study area in 2019 and 2 ppt increment isohaline contours.
Figure 6. Difference in annual salinity 2019 and (2013 to 2018 average).
Modified Chatry Optimal Oyster Salinity (MCOOS)

MCOOS analysis resulted in 3 km$^2$ (720 acres) of the study area designated as Class 1 (the highest ranked class) and 250 km$^2$ (61,832 acres) designated as Class 2. Much of the region designated as suitable (Class 1 or 2) was found north of the MRGO off of the eastern edge of Biloxi Marsh, extending into Chandeleur Sound, but the eastern extent of the suitable region is likely limited by hypoxia. Areas suitable for oysters ranged from just gulfward of Morgan Harbor Pass near Comfort Island, to Breton Sound gulfward of the MRGO, and in Mississippi Sound near Ship and Deer Islands, the coastlines of Portersville and Grand Bays, and the region between Petit Bois Island and the mainland (Figure 9).

![Figure 7](image-url)

Figure 7. MCOOS classifications in the study area for 2019. Classes 1 and 2 are considered as representing favorable conditions for production of seed oysters to a density that would support commercial industry, Class 3 as sub-marginal but still suitable for oysters, and Class 4 as generally unsuitable for oysters.
Modified Soniat Optimal Oyster Salinity (MSOOS)
MSOOS analysis resulted in 196 km² (48,404 acres) of the study area designated as Class 1 (the highest ranked class) and 1,767 km² (436,579 acres) designated as Class 2. Most of the area designated as suitable (Class 1 or 2) was found north of the MRGO in eastern Mississippi Sound and Chandeleur Sound, but the eastern extent of the suitable region is likely limited by hypoxia. Class 1 and 2 areas ranged from eastern Mississippi Sound near Mobile Bay, following the Mississippi barrier islands into Chandeleur Sound near the eastern edge of Biloxi Marsh, surging gulfward past the tip of the MRGO, and crossing the southwestern region of the Chandeleur Islands into the Gulf of Mexico (Figure 10).

Model Comparisons
Lakes Maurepas and Pontchartrain were delineated as Class 4 by both the MCOOS and MSOOS analyses. Lake Borgne and most of Biloxi Marsh were also described as Class 4, but the suitability improved in Mississippi Sound and areas near Lake Eloi, Treasure Bay and Morgan Harbor as the 2019 mean annual salinity climbed above fresh water concentrations. The MSOOS analysis was
overall more inclusive of lower polyhaline conditions (18-25 ppt) in Mississippi Sound than the MCOOS analysis, likely resulting from the inclusion of higher salinity conducive to spawning in the HSI formulation (Figures 9 & 10). The areal extent of suitable aquatic area was greater in the Biloxi Marsh sub-region in comparison to the Breton Sound sub-region for both the MCOOS and MSOOS analyses in 2019, and Class 4 (unsuitable) was the largest class for both analyses regardless of sub-basin (Figure 11). Additionally, the MCOOS suitable areas were smaller than the MSOOS suitable areas, and much of the MSOOS suitable areas were located down estuary from the public seed grounds (Figure 12).

![Figure 9. Areal extent (km²) of 2019 MCOOS and MSOOS classifications in aquatic regions of Biloxi Marsh Sub-basin and Breton Sound Sub-basin.](image-url)
Figure 10. MCOOS and MSOOS delineations of favorable conditions (Class 1 or 2) for oysters in the study area in 2019. *The areas scheduled for de-authorization in Bay Eloi and North Breton are not included in the Public Oyster Seed Ground shape.
Centroids
The MCOOS and MSOOS 2019 centroids were both located east of Biloxi Marsh, but the MCOOS centroid was positioned closer to Breton Sound (Figure 13). The MCOOS 2019 centroid shifted southeast 30.9 km away from the previous year’s centroid. The MSOOS 2019 centroid shifted southeast 12.9 km away from the previous year’s centroid. The MCOOS analysis did not classify any areas of Biloxi Marsh as Class 1 or 2 in 2017; consequently, there is no centroid for that year.

Figure 11. Migration of MCOOS (Class 1 or 2) and MSOOS (Class 1 or 2) centroids in Biloxi Marsh Sub-basin from 2013-2019. Centroids represent the delineations’ center and exhibit the movement of environment characterized as suitable for eastern oysters throughout time. Note: red line highlights the lack of a 2017 centroid.
Comparison to 2018
The percentages of different classifications of each sub-basin area were compared instead of areal extent. The areal extent of MCOOS Class 1 or 2 in the Breton Sound Sub-basin decreased by 2% of the basin from 2018 to 2019, and MSOOS Class 1 or 2 decreased by 14% of the basin from 2018 to 2019 developing gulfward from the prior year. In 2019, favorable conditions (Class 1 or 2) in Biloxi Marsh Sub-basin decreased by 5% of the basin using the MCOOS analysis, and 23% of the basin using the MSOOS analysis from their 2018 areal extents (Table 3; Figures 14 & 15).

Table 3. Areal extent (km²) and percentage of total study sub-basin aquatic areal extent (%) of MCOOS and MSOOS (Classes 1 or 2) classifications in Breton Sound Sub-Basin and Biloxi Marsh Sub-Basin in 2018 and 2019.

<table>
<thead>
<tr>
<th>Year</th>
<th>Breton Sound Sub-basin</th>
<th>Biloxi Marsh Sub-basin</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>MCOOS</td>
<td>MSOOS</td>
</tr>
<tr>
<td>2018</td>
<td>75 km² (3%)</td>
<td>300 km² (14%)</td>
</tr>
<tr>
<td>2019</td>
<td>19 km² (1%)</td>
<td>0 km² (0%)</td>
</tr>
</tbody>
</table>
Figure 12. MCOOS regions of favorable conditions (Class 1 or 2) in Biloxi Marsh and Breton Sound Subbasins in 2018 and 2019.
Figure 13. MSOOS regions of favorable conditions (Class 1 or 2) in Biloxi Marsh Sub-basin and Breton Sound Sub-basin in 2018 and 2019.
Reoccurrence of Favorable Conditions (Class 1 or 2) from 2013-2019

Combining the favorable regions of the MCOOS, and MSOOS analyses from 2013-2019 depicted a wide variation in areas designated as favorable for oysters (Figures 16 & 17) however, the regions were mainly restricted to specific areas in the Pontchartrain Basin (i.e. Chandeleur Sound near eastern Biloxi Marsh, lower Breton Sound Estuary, and waters 20-40 km east of the Mississippi River). Analogous to trends in the annual analyses, outcomes of the MSOOS analysis included more saline waters in the Biloxi Marsh and Breton Sound in comparison to those of the MCOOS analysis. MCOOS analysis results regularly (at least 4 years) classified an area of approximately 14.9 km² as Class 1 or 2 from 2013-2019. MCOOS Class 1 or 2 regions exhibited an overall mean salinity of 14.3 ± 0.6 ppt and ranging from 11.3 ppt to 14.3 ppt. MSOOS analysis results regularly (at least 4 years) classified an area of 946.6 km² as Class 1 or 2 from 2013-2019. MSOOS Class 1 or 2 regions exhibited an overall mean salinity of 17.1 ± 2.8 ppt and ranging from 9.9 ppt to 23.3 ppt (Figure 16; Supplementary Tables 1 & 2). (Note: areas computed are areal extent of aquatic study area.)
Figure 14. Sum of years from 2013-2019 depicting favorable areas for oysters (Class 1 or 2) by the MCOOS analysis. *Note that 2017 Class 1 or 2 area was confined to a small region in Breton Sound thus accounting for the lack of any 6-year favorable regions, and 2019 suitable regions only overlapped with 1 other year maintaining the maximum of 5 years of suitability in any given area.
Figure 15. Sum of years from 2013-2019 depicting favorable areas for oysters (Class 1 or 2) by the MSOOS analysis.
Oyster Fleet Surveys
A total of 111 active oyster boats were observed during four observation flights in the study area in March – August of 2019. Observed oyster fleet activity was generally low (at or below 1 boat / km²) throughout the study area. Density was 0 - 0.5 boats / km² on public seed grounds (not including the areas scheduled for de-authorization), most of which was located in the eastern fringes of Biloxi Marsh, reaching into West Karako and Three Mile Bays. *(Figure 18)* Fleet concentration was more widespread on the private leases of Biloxi Marsh, reaching from West Karako Bay to Lake Athanasio, and across into northern Breton Sound. *(Figure 19)* The strongest concentration of fleet activity was observed in Christmas Camp Lake on private oyster leases (0.5 – 1.0 boats/km²). Fleet activity south of the MRGO in Breton Sound was observed only in low density ranging from the MRGO to Lake Jean Louis Robin *(Figures 18 & 19)*.

During the floods of 2019 some oyster reef mortality was reported west of the Mississippi River however, the highest loss was concentrated east of the river in Biloxi Marsh where LDWF reported that much of the region experienced 100% mortality (notes from LDWF presentations at 2019 Oyster Task Force Meetings). Louisiana Department of Health (LDH) areas 1 and 2 experienced 100% mortality, and area 3 mortality was at 60 – 80% (personal communication Carolina Bourque of LDWF). At the same time, some oystermen reported that oysters survived the catastrophe in the area between Bayou la Loutre and the MRGO. In June of 2019, Governor Bell Edwards declared a state of emergency for Louisiana’s fisheries, and requested disaster assistance *(Fisheries SOE)*. Concern was expressed at several Oyster Task Force meetings that due to the timing of the event being after much of the harvest had already been collected, Louisiana did not yet meet the necessary loss of revenue (35%), so the oystermen may not qualify for disaster relief funding. Since material losses (culch and juvenile oysters) weren’t taken into account in the revenue calculations, the loss will not return as fast as other commercial value species (it can take 18 months - 3 years for an oyster to grow into commercial size). NOAA’s response to this concern was that the oystermen could reapply for funding each subsequent year as those losses are reflected in dockside revenue losses.
Figure 16. Cumulative Oyster boat density (boats/km²) observed on public seed grounds in Pontchartrain Basin in 2019. *The areas scheduled for de-authorization in Bay Eloi and North Breton are not included in the Public Oyster Seed Ground shape.
Hypoxia
Reoccurring hypoxia (<2mg/L) was observed in both Chandeleur and Breton Sounds. Hypoxia was observed annually in the northeast region of Chandeleur Sound throughout the ten years of monitoring. Hypoxia was observed in the area east of the Chandeleur Islands when sampled in 2011 (Figure 20). Occasional Hypoxia (observed less than 50% of years) coincided with 127 km² of MCOOS Class 1 or 2 (2019), and frequent hypoxia (observed more than 50% of years) coincided with 56 km² of MCOOS Class 1 or 2 regions. Occasional Hypoxia coincided with 800 km² of MSOOS Class 1 or 2 (2019), while frequent hypoxia coincided with 64 km² of these classes (Figure 20). Breton Sound has a potentially well-mixed, shallow bathymetry, often less than 10 feet deep, that may experience hypoxia in areas affected by the outflow of the Fort St. Philip diversion. LPBF survey data associates the pycnocline depth with hypoxia in Chandeleur Sound and suggests that frequent hypoxia is most likely to be observed in bathymetric regions greater than 10 feet (Figure 21).
Figure 18. Frequency of observed hypoxia in Chandeleur and Breton Sounds delineating regions of occasional (>50% of years) and high frequency (100% of years). Triangles represent sampling points. Chandeleur Sound was sampled from 2008-2019 (excepting 2009) and Breton Sound was sampled from 2013-2019. LPBF added a sampling transect in 2018 to extend the Hypoxia monitoring in Pontchartrain Basin.
Figure 19. Diagram showing potential pycnocline drivers in Breton and Chandeleur Sounds.
Louisiana Public Seed Grounds
In 2019 two areas, in Bay Eloi and North Breton Sound were scheduled to be de-authorized as public seed grounds in Phase IV of the lifting of the oyster lease moratorium, removing approximately 163 km² from the 2018 public seed ground total area. A focal analysis on those areas is included in the next section. Out of the 3,862 km² designated as public seed grounds, 771 km² (20%) were designated as MSOOS Class 1 or 2, and approximately 214 km² (6%) were designated as MCOOS Class 1 or 2. Approximately 1,256 km² (33%) of the public seed grounds were occasionally (< 50% of years) impaired by hypoxia, and 901 km² (23%) of the grounds were frequently (> 50% of years) impaired by hypoxia (Figure 22).

![Figure 20. MSOOS and MCOOS (Class 1 or 2 in 2019) delineations coinciding with Louisiana Public Oyster Grounds and regions of hypoxia observed 50% and 100% of sampling years. *The areas scheduled for de-authorization in Bay Eloi and North Breton are not included in the Public Oyster Seed Ground shape.](image)

**Figure 20.** MSOOS and MCOOS (Class 1 or 2 in 2019) delineations coinciding with Louisiana Public Oyster Grounds and regions of hypoxia observed 50% and 100% of sampling years. *The areas scheduled for de-authorization in Bay Eloi and North Breton are not included in the Public Oyster Seed Ground shape.

**Louisiana Public Seed Grounds designated for de-authorization**
In 2019, the Louisiana Department of Wildlife and Fisheries Commission amended Rule LAC 76:VII.511, to remove the public seed ground authorization from roughly 40,248 acres (roughly 163 km²) in the western region seed grounds located east of the MRGO in Bay Eloi, and in North Breton Sound upon commencement of Phase I of the lifting of the oyster lease moratorium (Figure 23). They were set aside for leasing (first lottery) during the lifting of the moratorium on new oyster
leases. Out of the 163 km² of public seed grounds scheduled to be de-authorized, Bay Eloi composed about 83 km² and North Breton Sound made up the remaining 80 km². Neither the MCOOS nor MSOOS analyses showed favorable conditions for the de-authorized areas in 2019, however the MSOOS analysis had a high frequency of favorable conditions from 2013-2018. Less than 1 km² (<1%) of the Bay Eloi area was designated as favorable (Class 1 or 2) using the MCOOS (2013-2019) analysis for 4 years, 3 km² (4%) for 3 years, 36 km² (43%) for 2 years, and 40 km² (47%) for 1 year. The (2013-2019) MSOOS analysis showed recurring favorable (Class 1 or 2) designations of almost 9 km² (10%) for 6 years, 57 km² (67%) for 5 years, 18 km² (21%) for 4 years, just over 1 km² (2%) for 3 years and less than 1 km² (<1%) for only 1 or 2 years. Using the MCOOS (2013-2019) analysis 3 km² (4%) of the North Breton Sound area was classified as favorable for 3 years, 28 km² (35%) for 2 years, and 46 km² (57%) for just one year. The MSOOS (2013-2019) analysis showed 5 years of recurring favorable conditions for oysters in 47 km² (59%) of the North Breton Sound area, 29 km² (36%) for 4 years, 3 km² (4%) for 3 years, and 1 km² (1%) for only 1 or 2 years. Sampling from 2013-2019 showed that roughly 33 km² (41%) of the North Breton Sound area is occasionally (< 50% of years) impaired by hypoxia, and 11 km² (14%) was frequently (> 50% of years) impaired by hypoxia. None of the Bay Eloi area was sampled for hypoxia from 2013-2019, and only 36 km² (45%) of the North Breton Sound area was sampled (Figures 24, 25, & 26).
Figure 21. Louisiana Public Oyster Seed Grounds to be de-authorized in Phase I of the lift on the oyster lease moratorium.
Figure 22. 2013-2019 analyses: MCOOS recurring favorable conditions (Class 1 or 2), frequency of recurring hypoxia, and the public seed grounds scheduled for de-authorization.
Figure 23. 2013-2019 analyses: MSOOS recurring favorable conditions (Class 1 or 2), frequency of recurring hypoxia, and the public seed grounds scheduled for de-authorization.
Figure 24. Areal extent km$^2$ of MCOOS and MSOOS 2019 classifications in aquatic regions public oyster seed areas scheduled for de-authorization.
Discussion

Delineations of optimal oyster habitat in the Biloxi Marsh Sub-basin in 2019 are unlike those of any other year since 2013. This stark difference was likely driven by the extreme increase of freshwater inflow in the region from the Bonnet Carré Spillway, Mississippi River, Pearl River, and other tributaries (e.g. Amite River, Tickfaw River, and Tangipahoa River) that begun at the end of 2018 and persisted into the summer of 2019 (USGS water data, USACE Bonnet Carré). The areas consistently (at least 4 years) classified as favorable for oysters (Class 1 or 2) from 2013-2019 represented more saline conditions using the MSOOS analysis (overall mean of 17.4 ± 2.77 ppt) than the MCOOS analysis (overall mean of 13.77 ± 1.2 ppt). This discrepancy is likely due to differences in the design of the models and how favorable salinities are selected. The 2017 analysis was the only year from 2013-2018 not to classify any area as Class 1 using the MCOOS analysis. Habitat suitability modeling from 2013-2019 has consistently suggested that the areal extent of favorable oyster conditions is greater north of the MRGO relative to south of the MRGO. Relative to the 2018 analysis, 2019 analysis of the Pontchartrain Basin study area displayed decreases of 2% in the areal extent of favorable oyster conditions (Class 1 or 2) using the MCOOS analysis, and 1% using the MSOOS analysis.

Breton Sound Sub-Basin

Relative to 2018, results from the 2019 analysis in Breton Sound Sub-basin demonstrated decreases of 2% in the areal extent of favorable oyster conditions (Class 1 or 2 MCOOS) and 14% (Class 1 or 2 MSOOS). The 2019 MCOOS analysis classified 1% of Breton Sound Sub-basin as favorable for oysters, and this area was confined to the region of Breton Sound gulfward of the MRGO. The 2018 MSOOS did not indicate any of Breton Sound Sub-basin as having conditions favorable for oysters, and suitable conditions southwest of the MRGO were restricted to areas gulfward of the bird’s foot delta.

Biloxi Marsh Sub-Basin

Relative to 2018, results from the 2019 analysis in Biloxi Marsh Sub-basin demonstrated a decrease of 5% in the areal extent of favorable oyster conditions (Class 1 or 2 MCOOS) and a decrease of 23% (Class 1 or 2 MSOOS). The 2019 MCOOS analysis classified 8% of Biloxi Marsh Sub-basin as favorable for oysters and this area mainly encompassed the area of Chandeleur Sound east of Biloxi Marsh nearest to the MRGO. The 2019 MSOOS analysis delineated 23% of Biloxi Sub-basin as favorable for oysters and these conditions were concentrated in Chandeleur Sound east of Biloxi marsh. Hopkins & Lopez (2017) suggested that opening the Bonnet Carré Spillway along with riverine flooding can shift favorable oyster conditions eastward in Biloxi marsh. Spillway openings alter water quality and faunal communities in the immediate receiving area of Lake Pontchartrain, and the effect on salinity extends to surrounding water bodies (e.g. Lake Borgne, Mississippi Sound, Biloxi Marsh). Observed river flows in the first half of 2019 (Mississippi River, Amite River, Tickfaw River, Tangipahoa River, and Pearl River) that contribute freshwater to Biloxi Marsh, were higher than those seen in prior years, marking a prolonged freshwater event in the Pontchartrain Basin that can explain the differences in suitable salinity locales (Supplementary Figures 2, 3 & 4, LPBF Hydrocoast maps, USACE river gages).

Gunter (1953) studied the opening of the Bonnet Carré Spillway in 1937, 1945, and 1950. The study found that while oyster populations in western Mississippi Sound and northern Biloxi Marsh faced significant mortalities, oysters below these regions in Biloxi Marsh may have benefitted from openings. Floodwaters (e.g. Bonnet Carré Spillway, Pearl River flooding) introduced into the
waterbodies north of Biloxi Marsh freshen conditions in the marsh, which reduces the prevalence of oyster disease and the abundance of oyster predators (Gunter 1953, Gunter 1955, La Peyre et al. 2009, Beseres Pollack et al. 2011, La Peyre et al. 2013). While adult oysters may face mortalities, particularly when extreme flooding coincides with warmer months, the effect of lowered salinity on settling and recently settled oysters is not as severe (Priester 2016, Rybovich et al. 2016). Conditions tend to revert to mesohaline conditions within a month via tidal exchange with the waters surrounding Chandeleur and Mississippi Sound (Supplementary Figures 2, 3 & 4). This phenomenon allows the younger oyster population to flourish under reduced predation and disease, and has been linked to increased oyster landings within two years (Gunter 1953, Wilber 1992, Buzan et al. 2009).

The prolonged freshwater event of 2019 channeled fresh riverine waters into Biloxi Marsh and Mississippi Sound via Lake Pontchartrain and the Pearl River, and led to Governor John Bel Edwards procuring a federal fisheries disaster declaration that included Louisiana, Mississippi and Alabama (LPBF Hydrocoast maps, USACE river gages, Office of the Governor of Louisiana 2019). Although oysters are able to slow metabolic processes to sustain life by closing their valves when subjected to inhospitable environments, the success of this strategy is limited by many factors, including original body condition prior to the event as well as rate and magnitude of salinity change, and duration of the event (Butler 1949, Loosanoff 1953, Casas et al. 2018).

The damage to Louisiana’s fisheries was reported to be extensive, and resulted in massive oyster mortalities in southeast Louisiana reaching 100% in many areas east of the Mississippi River (LDWF 2019), excepting the areas south of Bayou la Loutre (e.g. Lake Athanasio and Eloi Bay). The CPRA constructed a living shoreline in the Eloi Bay area. The areas between MRGO and Bayou la Loutre appear to have been insulated from freshwater inundation as surveys performed by Dr. Megan LaPeyre at the CPRA living shoreline show presence of both juvenile (25 – 76 mm) and market size (>76 mm) oysters both before and after the floods. Five of the six reefs had at least 100 oysters / m² in December of 2019 indicating that there was good survival in the area (Figure 27). This highlights the importance of this region to potentially serve as source of oyster larvae for the surrounding reefs.
Interpreting the long-term relationship between oyster harvest and productivity in the Pontchartrain Basin is complicated by openings of the Bonnet Carré Spillway, and closures of public seed grounds to commercial oyster harvest. Louisiana’s Department of Wildlife and Fisheries will recommend closures when public oyster resources are endangered, which is decided through extensive monitoring of oyster populations prior to the opening of the season. A limited amount (0-0.5 boats/km²) of oyster harvesting was observed in lower Breton Sound Estuary, and fishing efforts were largely concentrated north of the MRGO in Biloxi Marsh. Closures in eastern Biloxi Marsh and south of the MRGO likely restricted the fishing of public seed grounds in Pontchartrain Basin to north of the MRGO below the Biloxi Marsh closure area in addition to mortalities caused by the 2019 extreme freshwater event. In concurrence, the 2019 observations of the oyster fleet indicated almost exclusive fishing activity on private leases (as opposed to public seed grounds), and substantiates HSI model predictions that conditions north of the MRGO in Biloxi Marsh were more favorable for oyster production than south of the MRGO.

Model Comparisons
The Pontchartrain Conservancy has analyzed oyster habitat suitability in the study area from 2013-2019. The purpose of using both MSOOS and MCOOS methodologies was to compare the outcomes of the analyses. The findings of the current study echo those of the previous years in that the delineation of favorable oyster conditions with the MSOOS analysis resulting in suitability in more saline areas relative to the results of our MCOOS analysis (Preau et al. 2016, Hopkins and Lopez 2017, De Santiago and Lopez 2018, Denapolis and Lopez 2019). Additionally, the effects of the extended opening of the Bonnet Carré spillway in 2019 can easily contrast against prior years’
analyses demonstrating the effects of sudden, prolonged freshwater inundation (Supplementary Figures 1 & 2).

The 2019 divergences from the Chatry OSR are illustrated in Figure 28, which plots the monthly mean surface salinity of MSOOS, and MCOOS Class 1 for 2019. The Chatry OSR is included as a reference. The areas delineated as Class 1 by the MSOOS analysis generally had monthly mean salinity greater than MCOOS Class 1 throughout the year (excepting January and March), with greater differences in the summer. MCOOS Class 1 followed a slightly more similar trend relative to Chatry OSR, but the difference was greatest in April. Annual mean salinity for MSOOS Class 1 was 16.6 ppt in 2019, MCOOS Class 1 was 13.2 ppt, and the Chatry OSR is 13.7 ppt. The models’ applicability and design must be considered when comparing classifications of favorable salinity.

Figure 26. Overall monthly mean salinity (ppt) derived from MCOOS and MSOOS Class 1 delineations in 2019 and Chatry’s Optimum Salinity Regime (Chatry OSR). MSOOS Class 1 (2019) salinities were consistently higher (excepting January) than the Chatry OSR (1971-1981), while the MCOOS Class 1 (2019) salinity followed it more closely and was often lower.

The Chatry et al. (1983) derived MCOOS model incorporates the observed (empirically-derived) optimal conditions for maximum seed production of the following year from a ten-year period in
Breton Sound. These observations were restricted to the range of salinities observed at existing oyster reefs in Breton Sound (Black Bay, Bay Gardene, and California Bay) from 1971-1981. The monthly salinity requirements of various oyster life stages including reproduction, development, settlement, and survival are incorporated, but only as they would relate to the production of seed oysters the following year. For example, the study recognized summer salinity (June-September) as an important factor governing the abundance of oyster spat, with no settlement occurring at mean summer salinity <10 ppt (June-September) and peak abundance occurring at 20-22 ppt (≈11 spat/cm²). The authors found that seed oyster production shared an inverse relationship with spat abundance when mean summer salinities were greater than 12 ppt, and credited the relationship to the increased predation of oyster spat in more saline waters (>18 ppt). The production of seed oysters the following year was therefore greatest when mean summer salinities ranged from 12.2 ppt to 17.4 ppt, which was less than that observed to be optimal for spat settlement (Table 1).

Additionally, MCOOS and MSOOS delineations extend into Chandeleur Sound which likely attributed to the large amount of freshwater from sources in flood (e.g. Mississippi and Pearl Rivers, Bonnet Carré spillway) in 2019.

In regard to the discrepancy between MSOOS and MCOOS, Dr. Soniat (personal communication with LPBF staff scientist Kevin DeSantiago) commented:

“This is due to the requirement in the Soniat model that summertime salinities be favorable for reproduction. The Soniat model thus tries to determine where oysters cannot just survive long-term but reproduce. Suitable habitat thus includes a reproductive component. It does not deny that oysters can exist where they cannot reproduce. There are populations in low salinity that rely on reproduction of adults in, and advection of larvae from high salinity waters."

The MSOOS model incorporates the optimal conditions for spawning and the setting of larvae for the eastern oyster, and these values are derived from the respective literature and field-validated models from multiple regions of the species’ geographical range (Cake 1983, Soniat & Brody 1988, Denapolis 2018). While the optimal conditions delineated by the Modified Eastern Oyster Habitat Suitability Index Model (Denapolis 2018, Table 2) require that conditions during warmer months (May-September) be favorable for reproduction and larval settlement, it does not exclude areas that are subject to frequent hypoxia. It also recognizes that the development of oyster populations (non-commercial harvest density) in areas designated as sub-optimal (Classes 3 and 4) can be sustained when optimal conditions for spawning and larval setting are nonexistent via the transport of larvae from spawning oysters in higher salinities (Soniat, personal communication).

Soniat’s optimal range of mean spawning salinity V₂ (Figure 29, May-September) mirrors the observations of Chatry et al. (1983) for the setting of oyster larvae (Table 1, June-September); however, the Chatry OSR incorporates the potential influence of predators on the survivability of young oysters when the mean salinity of warmer months (June-September) is ~18 ppt (Figure 29).

The MSOOS alterations to the SOOS model further accounted not only for the detrimental effects of the combination of low salinity and high temperatures, but also established additional limitations for the effects of high temperatures with high salinity in the V₂ Min/Max SI variables, thus more comprehensively accounting for predation and disease impacts than prior analyses. Although a higher mean salinity during warmer months is optimal for oyster reproduction and setting, the sustainability of oyster populations in areas with consistently high salinities (>18 ppt) may be limited when mortality arising from predation and disease counteracts the recruitment of adult
oysters into the population. Due to the dynamic nature of estuarine systems, the locality of conditions favorable for sustaining oyster populations is expected to shift across the estuary in response to various natural and anthropogenic factors that govern salinity regimes in estuarine systems. Areas where mean salinity during the warmer months is consistently maintained at or above 18 ppt over multiple years may not be favorable for self-sustaining oyster populations and future restoration efforts.

The timing of unfavorable conditions is critical to determining the impact on oyster populations. This is particularly important during warmer months, when unfavorable conditions are more likely to influence oyster reproduction, setting, disease, and predation. The effect that deviation from Chatry’s OSR has on suitability values is not temporally weighted, therefore deviations can be concentrated during warmer months (Figure 28, Tables 1 & 2), which is when conditions are most influential on the reproductive processes of oysters, settlement of oyster larvae, and resulting production of seed oysters the following year (Chatry et al. 1983). Similarly, the Soniat 2012 model does not restrict the selection of the minimum monthly salinity (V3), or the proxy for killing floods, to warmer months; however, the MSOOS model integrates the synergistic effects of salinity and temperature on oyster populations.

The Modified Eastern Oyster Habitat Suitability Index Model (Denapolis 2018) is an important tool in analyzing the suitability of oyster habitat in response to events that can influence salinity (e.g. floods, droughts, fresh water diversions), but the model could be improved by including the effects of hypoxia. Addressing this omission may enhance modeling to identify areas for potential oyster
reef restoration efforts, relocation of state-leased oyster grounds, and to more accurately predict
the effects of future diversions.

**Implications for Public Oyster Seed Grounds scheduled for de-authorization**
The areas of Louisiana Department of Wildlife and Fisheries’ public oyster seed grounds scheduled
for de-authorization fell in recurrent favorable classification zones for MCOOS and MSOOS analyses
(2013-2018) with little reoccurrence of hypoxia observed from 2013-2019. However the gulfward
shift in suitable areas in the 2019 analyses did not classify these areas as suitable (**Figures 24 & 25**).
The region was classified as MSOOS Class 3 ("marginal") (**Figure 10**), and was the only significant
area with prior significant oyster productivity (and generally good HSI) that was classed this well in
2019. There is strong evidence that north of the MRGO within the Bay Eloi area there was good
oyster survival in 2019, as seen in the monitoring of the living shoreline demonstration project (PO-
148) (**Figure 27**), and reported by a local commercial oyster fisher in Lake Athanasio. It seems likely
that this area may not have spawned in 2019 because of low salinity, but salinity was high enough
to have strong survival. These conditions, even with the unprecedented freshwater event of 2019,
suggest that the areas in Bay Eloi and North Breton Sound scheduled for de-authorization should be
capable of supporting oyster reefs to a commercial harvest density if all other biological and
environmental needs are met.

**Implications for Restoration**
The temporal variation of favorable oyster conditions in the Pontchartrain Basin (**Figures 16 & 17**)
emphasizes the need to create, maintain and/or conserve suitable oyster habitat across gradients in
the estuarine system; but this is challenged by the need to restore deltaic processes with sediment
diversions. Areas with high reoccurrence rates of favorable conditions consistently favor oyster
spawning and the production of seed both naturally, and through means of cultivation. On the
contrary, areas with lower reoccurrence rates of favorable conditions represent areas where oyster
populations could only occasionally contribute to the region’s larval oyster pool. Maintaining oyster
populations in these areas increases the likelihood that oysters will be present and can supply
larvae into the estuarine system when favorable conditions for spawning are met. Extreme events
such as the 2019 extended opening of the Bonnet Carré spillway further interrupt viability of
regularly productive oyster reefs in the Biloxi Marsh and surrounding areas. Furthermore, if extreme
freshwater events become more frequent in the future, consideration of the regions deemed
suitable by the 2019 analysis may be significant for successful restoration efforts. Preserving an
abundant presence of oysters across the estuary ensures that surrounding reefs can aid in
reestablishing oyster populations following extreme events or prolonged unfavorable conditions
(Butler 1954, Melancon & Barras 1998). Oyster populations in the lower estuary can repopulate
decimated oyster populations in the upper estuary following extreme or prolonged freshwater
flooding, and reciprocally, oysters in the upper estuary can repopulate oyster populations in the
lower estuary during prolonged droughts.

The closure of the MRGO in 2009 has facilitated the reestablishment of the surrounding
waterbodies’ salinity regimes towards those that predate the completion of the MRGO in 1968
(Payne 1914, Owen 1955, Rousefell 1964, Henkel et al. 2017, **Figure 2**). A reduction in saltwater
entering waterbodies north of the MRGO (i.e. Lakes Borgne, Pontchartrain, and Maurepas) has
reduced the salinity in this region. While this shift in conditions supports the development of pre-
MRGO species (e.g. *Rangia* sp. and swamp forests) (Henkel et al. 2017), they may be less favorable
for species with higher salinity requirements such as oysters. Since the closure of the MRGO, the
nature of conditions as they relate to oyster habitat is likely on a trajectory to resemble those that existed prior to the construction of the MRGO. Furthermore, the role of other influences in the region (e.g. Pearl River, Bonnet Carré Spillway, Amite River, Tickfaw River, Tangipahoa River and diversions) may be more influential on salinity regimes following the closure of the MRGO.

**Analysis Limitations**

Inclusion of CRMS surface salinity data in the formulations of salinity surfaces would enhance the accuracy of the rasters that are used to calculate both the MCOOS and MSOOS analyses. Additionally, surface salinity data was used for all three analyses whereas bottom salinity is a driving force of habitat suitability for oysters in regions where stratification occurs, and surface salinity may not be equivalent to bottom salinity in Chandeleur, Breton, and Mississippi Sounds where stratification has been recorded. While this analysis may misrepresent the suitability of deeper, stratified areas, it should prove useful for habitat evaluation when considering reef construction in shallow waters where the reef can extend up into the water column where water is well mixed.

**Future Work**

Annual reporting and analyzing trends across multiple years is critical to understanding oyster populations. Analyses of oyster habitats from 2013-2019 presented various events that have the potential to influence oyster productivity and suitability (e.g. river flooding, opening of the Bonnet Carré Spillway). Continued monitoring efforts, such as those provided by LPBF’s Hydrocoast and its various contributing sources, is critical to understanding the dynamics of habitat suitability throughout time and various atmospheric, anthropogenic, and hydrologic events. Although available data can be limiting, the findings of this report analyses concur with our understanding of water quality conditions in the Pontchartrain Basin. Extensive monitoring of the environment is critical to understanding the relationship between key fishery species and future restoration projects. LPBF has increased its hypoxia monitoring efforts to include sites in the northern Biloxi Marsh in 2018 (Figure 20). Increasing the extent of our monitoring will aid in understanding the magnitude, and temporal and spatial patterns of hypoxic conditions in the Pontchartrain Basin.

**Conclusion**

The methods used in this study define areas in Biloxi Marsh Sub-basin and Breton Sound Sub-basin as potentially suitable for oysters. However, the extreme freshwater event of 2019 shifted the suitable waters gulfward of the 2013 – 2018 regions. The massive flow of freshwater into the Pontchartrain Basin via the Mississippi and Pearl Rivers forced suitable waters away from established oyster reefs down estuary into Chandeleur Sound. Nevertheless, in agreement with isohalines depicted on LPBF Hydrocoast maps, the areas between the Bayou la Loutre ridge and the MRGO were insulated from the freshwater influx, and oysters there survived the freshwater event. This area may be significant for regional recovery of oysters and a potential source area for spat. Overall, results of both models from 2013-2019 suggest that the area of suitable oyster conditions is larger north of the MRGO compared to south of the MRGO. The MSOOS analysis selected for higher salinity compared to the MCOOS analysis, and included the influence of predation and disease.

LPBF oyster HSI analyses can potentially predict the effects of fresh water diversions on Louisiana’s eastern oyster populations, and thereby can be used as a tool for management. The devastating effects of the 2019 dual openings of the Bonnet Carré spillway emphasize a need to reassess management of the lower Mississippi River. LPBF has proposed a marsh creation project to narrow
Three Mile Pass to be assessed for the 2023 Coastal Master Plan which will alter the exchange of fresh and saline waters in Biloxi Marsh and Mississippi Sound (Figure 30).

Finally, hypoxia should be explored for suitable regions of Chandeleur and Breton Sounds to determine feasibility for future oyster restoration projects. Current and future hydrological condition, bathymetrical, and oyster population surveys should supplement future oyster reef restoration planning.

Figure 28. Proposed projects for 2023 Coastal Master Plan. #7 indicates the Three Mile Pass project.
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Supplementary Material

Supplementary Document 1 Comment Letter from LPBF to U.S. Fish and Wildlife Service

April 20, 2020

U.S. Fish and Wildlife Service
P.O. Box 29649
Atlanta, Georgia 30345

Re: Comments on LPBF Proposed Oyster Reef Corridors for the Draft Restoration Plan/Environmental Assessment #5: Living Coastal and Marine Resources (LCMR) – Marine Mammals and Oysters

Background: The Lake Pontchartrain Basin Foundation (LPBF) is very supportive of programmatic activity to construct successful oyster brood reefs in southeast Louisiana, and so we would like to share some technical data that may assist in the optimal siting of the final locations of potential brood reefs in this area. It is our suggestion to have brood reefs complement other oyster programmatic activities, such as the recently constructed reefs, and using the best available information on the environmental conditions for the last several years to maximize the propagation of oysters. Specifically, LPBF has salinity data, oyster HSI analyses, and oyster fleet activity that strongly suggest where oysters can successfully propagate in this region. For example, our most recent oyster report is “Habitat suitability analyses for the Eastern oyster, Crassostrea virginica, of the Pontchartrain Basin Estuary, Southeast Louisiana, in 2018”. This report summarizes our HSI and fleet surveys from 2013 to 2018. It does not include the extreme freshwater event of 2019, in which there were two openings of the Bonnet Carré Spillway, and multiple floods of the Pearl River. The “2019 freshwater event” may prove to be an extreme outlier type event, but it is still worth considering in contrast to normal annual salinity fluctuations seen over the last several years (discussed below).

Based on salinity, HSI and actual fleet activity, LPBF is convinced that there is an enormous opportunity to enhance propagation of oysters within and around the area of the Biloxi Marsh. It is this area that was historically productive (Pre-1960) prior to construction of the Mississippi River Gulf Outlet (MRGO), and this area has generally returned to being productive since the closure of the MRGO in 2009, in spite of impacts from the Deepwater Horizon in 2010. Restoration of the Biloxi Marsh oyster habitats also supports programmatic planning such as LPBF’s Comprehensive Management Plan, which was approved by the EPA.

Suggested brood reef corridors: The goal of an oyster brood reef is successfully subsidizing of surrounding oyster beds with oyster larvae as frequently as possible, and for as long as possible. Multi-year fluctuations in observed salinity, cause the regions of optimum oyster suitability, and productivity to move up or down estuary in southeast Louisiana. Therefore, we suggest “brood reef corridors” which span the annually shifting “sweet spot” and thereby, are more likely be collectively successful. Multiple annual HSI analyses (2013 to 2018) identify a specific spatiotemporal range of optimum salinity and the most suitable areas are independently corroborated with observed oyster fleet activity over several years. We suggest constructing brood reefs across the spatial variability, based on recurring suitable salinity. This would be for both survival (to avoid freshwater kills and marine predators and disease), and spawning (promoting the successful release of oyster larvae into the water column) in order to promote the success of the project. Proximity to the desired commercial oyster beds for spat set is also important.

The attached map shows the LCMR proposed brood reefs and cultch plant in SE Louisiana along with other critical information that may guide the exact siting of the brood reefs. The map also includes the LDWF / LPBF reefs (constructed in 2019), the public seed areas (modified in 2019), the HSI results (2013 – 2018), and the
extent of freshwater (<5ppt) during the 2019 freshwater event. The LDWF / LPBF reefs are all sub-tidal, and composed of reef balls, limestone rip-rap and oyster or _Rangia cuneata_ shell. Note that three of the LDWF/LPBF reefs are located in areas of potential oyster survival, but only one coincides with a region that is ideal for spawning, and so is within one of the suggested brood reef corridors.

The map highlights three suggested areas that could be developed as brood reef corridors (green ellipses) in the Biloxi Marsh that principally meet the following conditions:

- Areas are located within Louisiana public oyster seed grounds
- Areas were generally not observed to be hypoxic
- Areas were classified by the HSI (Modified Soniat Optimal Oyster Suitability) method as suitable (best classes) for oyster survival for multiple years (at least 4 of 7 years with good HSI).
- Areas are near to significant commercial oyster fleet activity (2013 to 2019)

In addition, all of the target brood reef corridors are near marsh. Two of the three areas suggested (green ellipses) are gulfward of the contour that defines the extent of freshwater inundation that lasted four months during the Bonnet Carré spillway openings of 2019. This has the potential advantage of evading mortality from extreme freshwater events should extreme freshwater events become a more regular occurrence. LPBF is currently completing our analysis of the oyster HSI for 2019, and a report should be released in the next couple of months.

We suggest the following criteria would enhance the efficacy of brood reefs. Reef substrate that is varied in height, and composed of clean, hard material of varying sizes (e.g. reef balls, limestone, oyster shell free of fouling organisms), would include interstitial space for the protection of growing juvenile oysters and enhance variation in habitat. Inclusion of larger sized substrate (e.g. reef balls or boulders) could discourage illegal harvest and be resistant to depletion or relocation from currents and wave action. Vertical relief reaching well into the water column would expose reef material to currents which would help to avoid potential hypoxic waters, transport food to the reef, and remove suffocating sediment, although areas with intense wave action can be detrimental to oyster reefs.

**Summary:** LPBF wholeheartedly supports the goals of constructing oyster brood reefs in southeast Louisiana. We hope that the data provided here assists agencies in selecting the best possible reef sites and consideration to site new brood reefs within these corridors. LPBF is available to provide further information that may assist with the important agency task of developing these projects.

Sincerely,

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LPBF - Oyster biologist
Tasia@saveourlake.org

**Attached:** Map of LPBF Suggested Brood Reef corridors in Southeast Louisiana
LPBF Suggested Oyster Brood Reef Corridors in Southeast Louisiana
**Supplementary Table 1. Aquatic areal extent and percentage of total study area for MSOOS and MCOOS by class analyses from 2013-2019.**

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<td>5356.2</td>
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Note: Study area size varies across years.
Supplementary Table 2. Aquatic areal extent of the number of years that areas categorized as most suitable by MCOOS and MSOOS analyses from 2013-2019 and the overall mean salinity and standard deviation and minimum and maximum salinity of those areas (2013-2019).

<table>
<thead>
<tr>
<th># Years</th>
<th>MCOOS (Class 1 or 2)</th>
<th>MSOOS (Class 1 or 2)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Areal Extent (km²)</td>
<td>Min. (ppt)</td>
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<tr>
<td>1</td>
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<td>11.3</td>
</tr>
<tr>
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Supplementary Figure 1 Overall monthly mean salinities (ppt) derived from MCOOS and MSOOS Class 1 delineations in 2018, 2019, and Chatry’s Optimum Salinity Regime (Chatry OSR). MSOOS Class 1 (2019) salinities were consistently higher (excepting January) than the Chatry OSR (1971-1981), while the MCOOS Class 1 (2019) salinities followed it more closely and was often lower. Excepting January, MSOOS Class 1 (2018) salinities were near or below the 2019 values, and MCOOS Class 1 (2018) salinities were below except for Aug – Nov 2018. The Bonnet Carré spillway was open from March 8-30, 2018 and from Feb 27-Apr 11, 2019 and again from May 10-July 27, 2019.
**Supplementary Figure 2** Overall monthly mean salinities (ppt) derived from MCOOS and MSOOS Class 1 delineations in 2015, 2019, and Chatry’s Optimum Salinity Regime (Chatry OSR). MSOOS Class 1 (2019) salinities were consistently higher (excepting January) than the Chatry OSR (1971-1981), while the MCOOS Class 1 (2019) salinities followed it more closely and was often lower. Excepting April, June and December, MSOOS Class 1 (2019) salinities were near or above the 2019 values, and MCOOS Class 1 (2015) salinities were below except for Aug – Nov 2015. The Bonnet Carré spillway was not open in 2015, and was opened twice in 2019 from Feb 27-Apr 11, and again from May 10-July 27.

<table>
<thead>
<tr>
<th>Method and Conditions</th>
<th>Month</th>
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<tr>
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<td>Chatry OSR</td>
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<td>MSOOS Class 1 (2015) Bonnet Carre Closed</td>
<td>18.9</td>
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![Graph showing mean surface salinity for different conditions and years.](chart.png)
Supplementary Figure 3 Monthly mean surface salinity in the study area for 2018.
Supplementary Figure 4 Monthly mean surface salinity in the study area for 2019.