Chapter 3
Apalachicola Bay

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Description of the region

Apalachicola Bay is the largest of several estuarine systems in the panhandle region of northwestern Florida. It is confined hydrologically by a network of four barrier islands and is divided into four sections: St. Vincent Sound, Apalachicola Bay proper, East Bay, and St. George Sound (Fig. 3.1). The system is connected to the Gulf of Mexico through three natural tidal inlets (Indian Pass, West Pass, and East Pass) and one man-made inlet (Government Cut, also known as Sike's Cut). The bay is in a transition zone between diurnal tides to the west and semidiurnal tides to the southeast, resulting in a mixed tidal regime with one to five tides daily (Huang 2010, Oczkowski et al. 2011, Huang et al. 2015). Tides can be strongly affected by wind and are normally less than 1 m (3.3 ft) in range. Water currents are tidally driven but can also be strongly impacted by river discharge and winds. Currents generally do not exceed 1 m s^{-1} (3.3 ft s^{-1}) except in passes and tidal cuts. The system is wide and shallow, with an average depth of 2–3 m (6.5–10 ft), resulting in well-mixed and well-oxygenated waters with little stratification. Bottom types consist largely of sand and other soft sediments, with hardbottom in the form of extensive oyster reefs (Edmiston 2008). Water temperature typically ranges annually from 5–32 °C (41–90 °F). Salinity varies widely spatially and temporally and can range from less than 1 to 33. Overall water quality conditions in Apalachicola Bay are excellent, in part because the panhandle region is one of the least populated coastal areas in Florida (Livingston 1984, 2015, Edmiston 2008).

The bay receives most of its freshwater inflow from the Apalachicola River, the largest river in Florida in terms of flow. Average seasonal discharges range from 570 m^3 s^{-1} (20,000 ft^3 s^{-1}) in late summer and fall to 1,800 m^3 s^{-1} (65,000 ft^3 s^{-1}) in early spring (Edmiston 2008, Huang 2010). More than 80% of the water in the Apalachicola River comes from the Chattahoochee and Flint rivers (Fig. 3.2), which converge at Lake Seminole and the Jim Woodruff Dam at the Florida/Georgia border to form the Apalachicola. The Chipola River also provides smaller volumes of water as a tributary to the Apalachicola. The watershed of the Apalachicola–Chattahoochee–Flint (ACF) river system encompasses roughly 50,500 km^2 (20,000 mi^2) in Florida, Georgia, and Alabama. More than 7 million people, including many residents of Atlanta, live in the ACF watershed and rely on it as a major source of fresh water for drinking, recreation, and agriculture (Camp et al. 2015). The ACF river system includes 16 dams built to control alluvial flow and prevent flooding (la Cecilia et al. 2016).

Because of its productivity, biodiversity, and water quality, Apalachicola Bay has been designated as an Outstanding Florida Water, State Aquatic Preserve, International Biosphere Reserve, and National Estuarine Research Reserve (NERR; Livingston 1984, Edmiston 2008). The region is within the Northwest Florida Water Management District (NWFWMD). The Apalachicola National Estuarine Research Reserve (ANERR), which

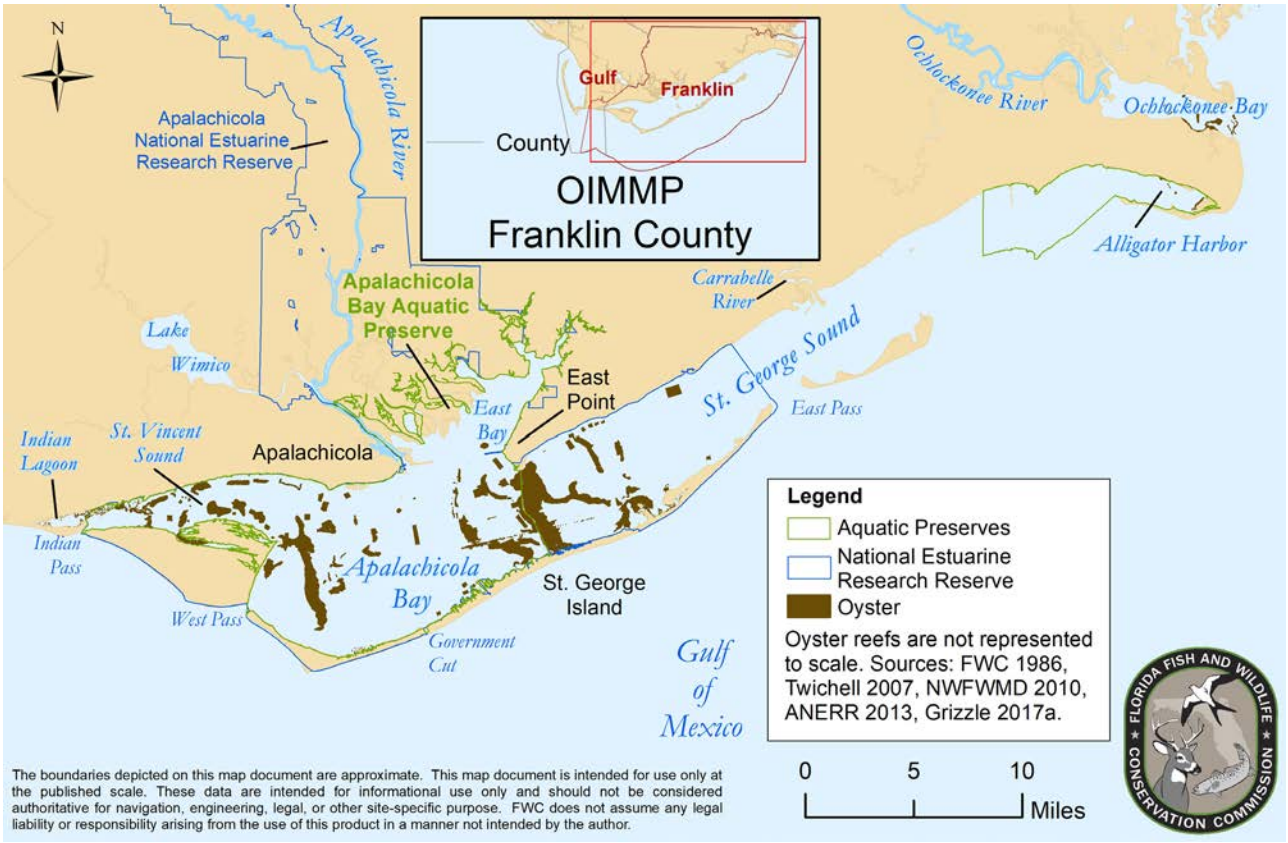

Figure 3.1. Major features of Franklin County, including the Apalachicola Bay estuarine system and oyster reef areas to the west (Indian Lagoon) and east (Alligator Harbor and Ochlockonee Bay). Oyster mapping sources: FWC 1986 (made from historical data and aerial photographs, years unknown), Twichell 2007 (from 2005–2006 side-scan sonar), NWFWMD 2010 (from 2009–2010 aerial photographs), ANERR 2013 (from 2007 and 2010 aerial photographs), and Grizzle 2017a (from 2012 satellite imagery).

encompasses roughly 1,000 km^2 (390 mi^2), spans the estuary and the lands surrounding the lower Apalachicola River (Fig. 3.1; FDEP 2014). Lands within ANERR are owned and managed by many partners including the Florida Fish and Wildlife Conservation Commission (FWC; Apalachicola River Wildlife Enhancement Area), NWFWMD (Apalachicola River Water Management Area), U.S. Fish and Wildlife Service (St. Vincent National Wildlife Refuge), the Florida Department of Environmental Protection's (FDEP's) Division of Recreation and Parks (St. George Island State Park), as well as FDEP's Florida Coastal Office (Apalachicola Bay Aquatic Preserve, Little St. George Island). Nearly the entire estuarine system provides potential habitat for the eastern oyster, *Crassostrea virginica*. The bay's history of providing most of the state's oyster harvest (until recently) is one indicator of how important oysters are in the bay's ecology and the region's economy. The extensive interstate watershed of the Apalachicola River, however, exacerbates the complexity of managing Apalachicola oyster resources.

Ecology of oysters in Apalachicola Bay

The autecology of oysters in the bay has been reasonably well studied (see summaries in Livingston 1984, Edmiston 2008). Spawning occurs mainly from April through October, typically with spring and fall peaks. Growth is continuous and rapid throughout the year, and market size (76 mm [3 in] shell height) is reached in approximately 18 months (Ingle and Dawson 1952). Oyster reefs cover perhaps 10% of the bay bottom and include both subtidal and intertidal reefs (Kennedy and Sanford 1989, Edmiston 2008). Subtidal reefs cover much more area than those in the intertidal zone, with 1,600–4,000 ha (Fig. 3.3; 4,000–10,000 ac) of subtidal oyster bottom mapped or estimated in recent decades (Livingston 1984, Twichell et al. 2007, ANERR 2013) compared to approximately 80 ha (200 ac) of intertidal reefs mapped in 2016 (Grizzle et al. 2017a). The intertidal reefs consist mainly of natural reefs, while the subtidal reefs consist of natural and planted reefs resulting from additions of clam shell,

Figure 3.2. Apalachicola–Chattahoochee–Flint River system (watershed boundary source: NERRS 2007).

fossil shell, and other hard materials to provide cultch (suitable substrate) for oyster larval settlement in support of the fishery (Berrigan 1990, Edmiston 2008, FDACS 2015a).

Based on extensive sonar mapping and field sampling, Twichell et al. (2010) concluded that the present-day subtidal reefs in the bay began to develop on the crests of broad, flat sand bars around approximately 400 BCE, most of which were oriented perpendicular to the long axis of the bay. The early reefs grew vertically and migrated westward, suggesting a net westward transport of sediments in the bay. This model contrasts somewhat with reef development in the Big Bend region to the south, where it is thought that oyster reefs initially developed on nearshore limestone outcrops (Hine et al. 1988). Core and seismic profile data indicate that oyster reefs were more extensive historically and have decreased at their edges due to fine sediment inputs from the Apalachicola River (Twichell et al. 2010). The current reef size and other characteristics reflect changes in the original spatial patterns resulting from more than two millennia of responses to changes in climate, sea level, water quality, sediment inputs from both freshwater and marine sources, and more recently by harvest and management practices.

Recent work has shown wide spatial variability in live oyster densities on both intertidal and subtidal reefs in the bay. The Florida Department of Agriculture and Consumer Services (FDACS) has annually monitored selected reefs in the bay for oyster density and size from 1990 to 2015, when monitoring responsibilities shifted to FWC (data summarized in Camp et al. 2015; also see Grabowski et al. 2017). From 1990 through 2011 (prior to the fisheries collapse discussed below), total oyster densities fluctuated between roughly 200 and 400 oysters/m^2 (19–37 oysters/ft^2). On intertidal reefs, Grizzle et al. (2017b) found an overall mean of ~400 oysters/m^2 (37 oysters/ft^2) in 2016 throughout the bay. However, the western and eastern portions of the bay differed greatly. Many intertidal reefs in the western bay were dead, and the overall mean density of live oysters was <50 oysters/m^2 (4.6 oysters/ft^2), compared with ~1,000 oysters/m^2 (93 oysters/ft^2) in the eastern bay. The same overall pattern was reported for subtidal reefs by Kimbro (2013).

Spatial patterns in mortality also vary widely across subtidal reefs in Apalachicola Bay (Berrigan 1988, Livingston et al. 2000, Edmiston 2008). For example, Livingston et al. (2000) produced maps of oyster mortality illustrating how river flow and salinity variations were related to mortality patterns across the bay in 1985 and 1986. Under moderate river flows, oyster mortality was reduced throughout the central portions of the bay. Under low-flow conditions, the area of high mortality in the outer bay increased. This effect is presumably because predators move from the Gulf of Mexico further into the bay when waters are more saline. The reverse—high river flows, such as during a hurricane—can result in essentially the opposite result with respect to spatial mortality patterns if salinity falls below the oyster's tolerance levels (Shumway 1996, Edmiston et al. 2008). The impacts of storms are more complicated, however, because storm-related factors other than salinity can increase oyster mortality. For example, Hurricane Elena in 1985 produced extreme tides, strong winds, heavy rainfall, and high river discharges that resulted in burial by sediments and other physical damage to reefs in western St. George Sound and eastern Apalachicola Bay (Berrigan 1988, 1990). Oyster production in most areas of the bay dropped by 90% following Hurricane Elena, resulting in closures to harvest, but rebounds in growth and recruitment quickly followed, particularly in areas with substrate restoration (Berrigan 1990). Edmiston et al. (2008) reviewed the literature on the impacts of subsequent storms on oysters in the bay, emphasizing that the effects of sporadic events such as

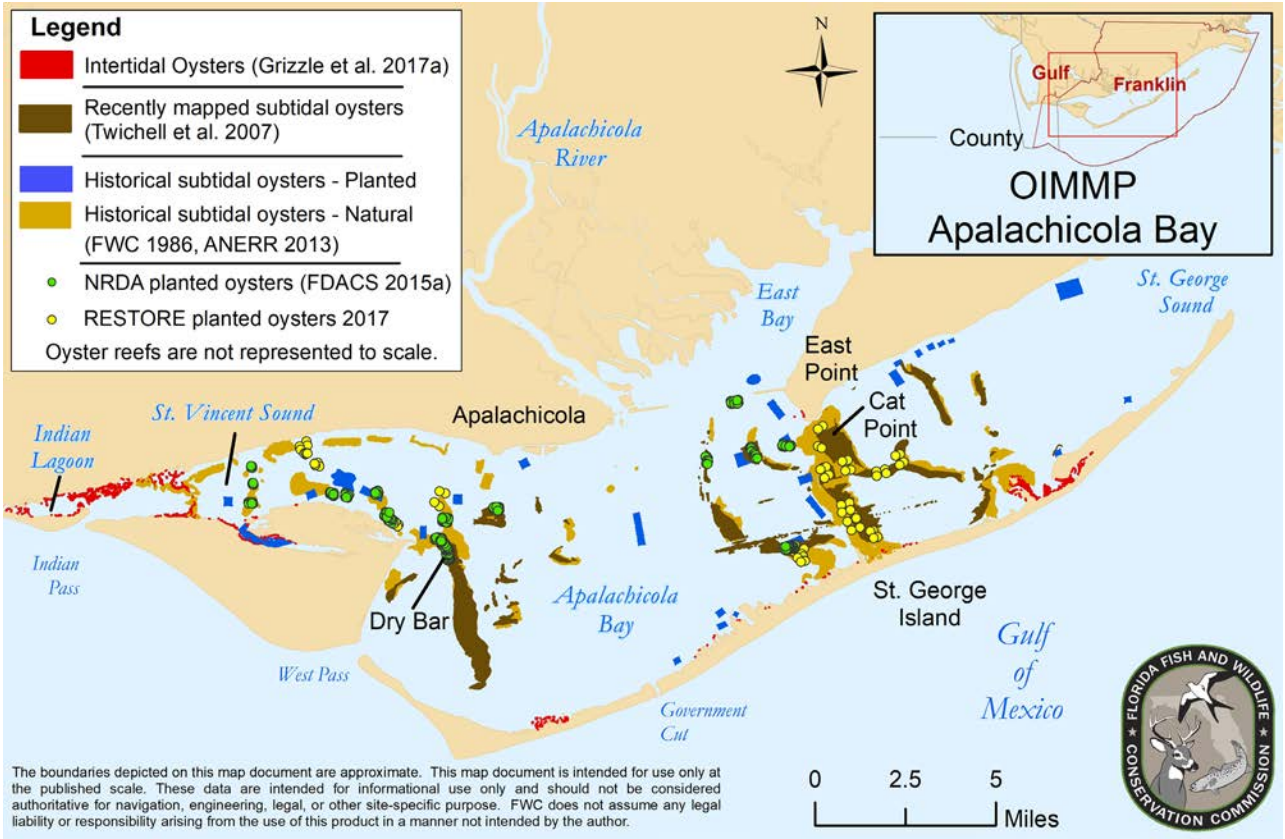

Figure 3.3. Extent of natural and planted subtidal reefs and intertidal reefs in Apalachicola Bay. Oyster mapping sources: FWC 1986 (made from historical data and aerial photographs, years unknown), Twichell 2007 (from 2005–2006 side-scan sonar), ANERR 2013 (from 2007 and 2010 aerial photographs), Grizzle 2017a (from 2012 satellite imagery), and planting sites from 2015 (FDACS 2015a) and 2017.

hurricanes can vary widely and involve multiple mortality factors. Thus, their effects are not easy to predict.

The spatial distribution of the bay's reefs today (Figs. 3.1 and 3.3) is a result of both natural processes and intensive management, which began in the late 1800s (Dugas et al. 1997; see review in Pine et al. 2015). Among the most important of the management actions was implementation of extensive shelling (shell planting) programs. It was soon recognized that loss of shell due to harvest threatened sustainability of oyster fisheries throughout Florida because it removed hard substrate needed for larval settlement. Shell additions to the bay were first recommended around 1885. The Florida Division of Agriculture planted the first known shell, 15,000 barrels' worth, in 1913. Shell distribution increased substantially around 1925 (P. Zajicek, FDACS, personal compilation from Biennial Reports of the Fish Commission, Biennial Reports Shellfish Division, Florida Department of Agriculture and Biennial Reports of the State Board of Conservation). Shell distribution continued more regularly after 1949 as the result of a State-mandated program requiring that harvested oyster shell be returned to public oyster beds, sometimes supplemented with limestone rock. Whitfield and Beaumariage (1977) wrote that as of 1977, more than 4 million bushels of shell and rock had been used to cover nearly 400 ha (1,000 ac) of bottom in Apalachicola Bay. Shell buy-back programs have been implemented to pay dealers for collected shell, but because these programs rely on grants, they do not have a permanent source of funding. Recent shelling programs have used primarily fossil shell (FDACS 2015a, 2015b).

Oyster harvesting in Apalachicola Bay

Much of the Apalachicola Bay system is classified by FDEP as Class II waters (those designated for shellfish propagation or harvesting) that are conditionally approved or restricted for harvest by FDACS dependent on prevailing water quality and seasonal closures (Fig. 3.4). Current oyster harvest regulation in Apalachicola Bay includes bag limits, size limits, and spatial closures. The oyster fishery is integral to the lives of many people living in the Apalachicola Bay region. Before the collapse, the fishery provided more than 2,500 jobs to nearby coastal communities, of-

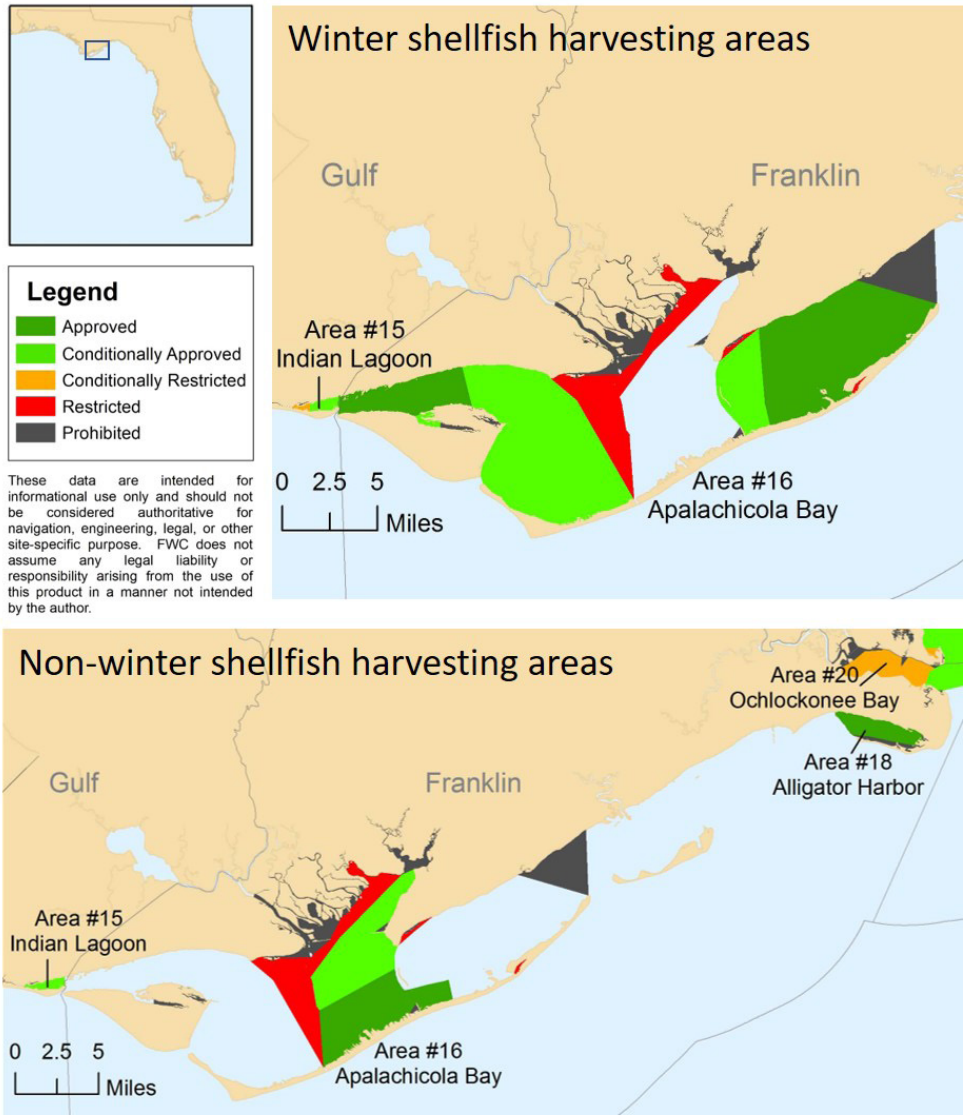

Figure 3.4. Shellfish harvesting areas within eastern Gulf County and Franklin County. Source: FDACS (2017a).

ten making up to half of their revenue (Havens et al. 2013, Camp et al. 2015). Harvest from portions of the bay in Franklin County has historically dominated oyster harvest in Florida, yielding more than 90% of the state's commercial landings (Fig. 3.5) and 10% of the oysters sold in the continental United States (Livingston 1984, Havens et al. 2013). Commercial landings data from 1895 to 1984 were reported by the U.S. Fish and Wildlife Service, Florida State Board of Conservation, Florida Department of Natural Resources, or National Marine Fisheries Service, but the FWC's Fish and Wildlife Research Institute took over these responsibilities in 1985. From 1986 onwards, FWC recorded the number of trip tickets and landings via a mandatory reporting system (Camp et al. 2015). Earlier, such data had been reported voluntarily. Despite the mandatory reporting system, Havens et al. (2013) found evidence of unreported harvest and harvest from closed areas that are difficult to quantify and reconcile with reported landings data.

Oyster landings from Franklin County (dominated by Apalachicola Bay) fluctuated but overall increased from 1950 through the early 1980s, peaking at 3,000 metric tons (6.6 million pounds) in 1981 (Fig. 3.5). In September 1985, Hurricane Elena caused extensive damage to the bay's reefs, particularly on the east end (Livingston et al. 1999; also see discussion above). Many of the reefs that had historically been the most productive suffered high mortality of live oysters, loss of cultch, and extensive sedimentation (Berrigan 1990). The bay was closed to harvest for several months for research and distribution of clam shells as substrate (Berrigan 1990). Commercial oyster harvest resumed in May 1986, but with harvest restrictions. Landings were nearly an order of magnitude lower than

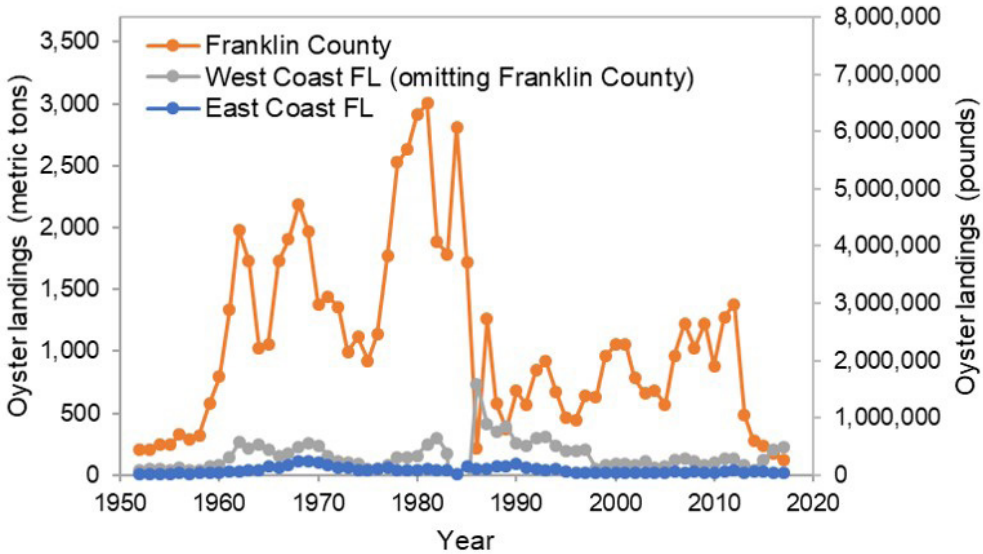

Figure 3.5. Commercial oyster landings for Franklin County and the east and west coasts of Florida. Oyster landings data before 1986 were collected under a voluntary reporting system. Data sources: 1951–1983, Florida Commercial Marine Fish Landings (see Appendix A); 1984–1985, Berrigan (1990); 1986–2017, FWC (2018).

the pre-hurricane harvest in 1985. Oyster populations recovered relatively quickly as a result of successful recruitment, shelling, and restricted harvests (Berrigan 1990, Livingston et al. 1999, Pine et al. 2015), but commercial harvests never returned to the levels recorded before Hurricane Elena (Fig. 3.5).

Landings as well as catch per unit effort (CPUE) estimates fluctuated, but generally increased, through the late 1980s and early 1990s (Fig. 3.6). Several hurricanes affected Apalachicola Bay after 1985; impacts to the oyster reefs and the fishery varied depending on storm-related physical disturbances and salinity extremes. In 1994, hurricanes caused record flooding in the region, resulting in near-freshwater conditions in the bay for nearly two weeks. While reefs were apparently not physically damaged by the hurricanes, mortality on the reefs varied from 10 to 100% as a result of low salinity (Edmiston 2008, Edmiston et al. 2008). Oysters at Dry Bar and St. Vincent reefs (Fig. 3.3) suffered particularly high mortality. In 2005, Hurricane Dennis caused a 3-m (10-ft) storm surge, but this had little impact on subtidal oyster reefs, as the extra water depth protected them from wave energy (Edmiston et al. 2008). Hurricane Katrina in 2005 did not have a measurable impact on the oysters, but hurricane winds pushed a red tide bloom into the bay, resulting in the closure of oyster harvesting for more than three months (Edmiston et al. 2008). Landings increased substantially after Katrina, but CPUE began to show a steady decline until the most recent collapse, in 2012. The impact of 2018's Hurricane Michael on Apalachicola Bay oysters was unknown when this report was written.

It should be noted that Apalachicola Bay was not directly affected by the Deepwater Horizon oil spill in 2010 (Grabowski et al. 2017). The fishery remained open—unlike those in large areas of Texas, Louisiana, and Alabama—and the shortage of oysters in other Gulf areas initially led to an increase in oyster harvesting and prices for oysters from Apalachicola Bay (Camp et al. 2015, Pine et al. 2015, Grabowski et al. 2017). Out of concern for possible future closures, the oyster harvesting season in Apalachicola Bay was opened early. While oyster harvesting is usually prohibited Friday through Sunday, harvesting was also allowed on weekends during that time (though no changes were made with regards to size limits or daily bag limits) (FWC 2013). Despite the extended season, oyster landings in 2010 were slightly lower than those before and after (Fig. 3.6), perhaps in part due to declining prices. Concern about the safety of post–oil spill Gulf oysters led to a decline in demand and oyster prices (Sumaila et al. 2012, Camp et al. 2015), though there has been no evidence that the oil spill contaminated seafood from Apalachicola Bay (Havens et al. 2013).

2012–2013 collapse of the oyster fishery

Oyster landings from Apalachicola Bay began a marked decline in 2012, dropping from 1,378 metric tons (3.0 million pounds) in 2012 to only 483 metric tons (1.1 million pounds) in 2013, followed by four years of historically low landings (Figs. 3.5 and 3.6). Fishery-independent sampling by FDACS has also shown a sharp decline

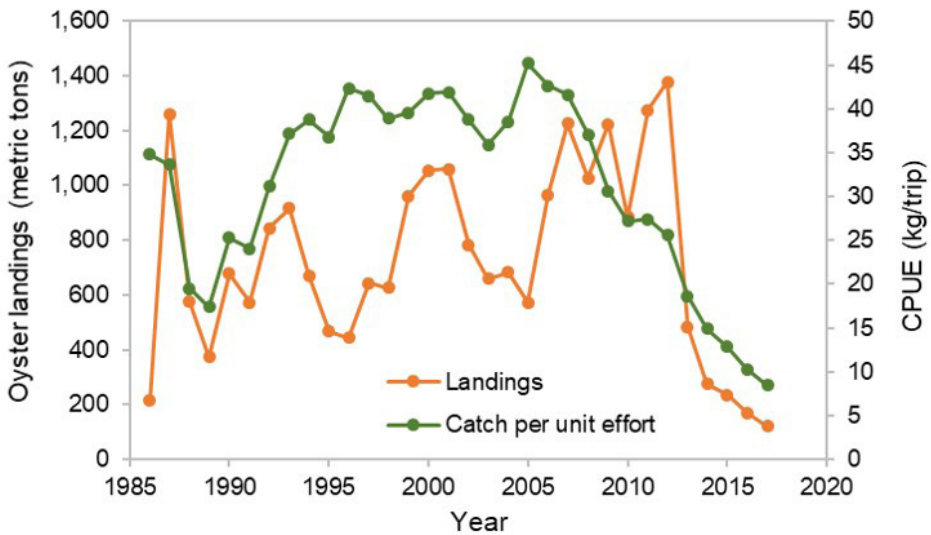

Figure 3.6. Commercial oyster landings and catch per unit effort (CPUE) data for Apalachicola Bay since 1985. Data source: FWC 2018.

in oyster density on subtidal reefs (results summarized in Camp et al. 2015). As previously mentioned, from 1990–2011 total oyster densities fluctuated between roughly 200 and 400 oysters/m^2 (19–37 oysters/ft^2). The density of oysters on subtidal reefs then fell below 100 oysters/m^2 (9 oysters/ft^2) during 2012 and 2013. Although many of the mapped subtidal reefs have not been monitored for density in recent years, a spatially extensive sampling program in 2016 by FWC found live oysters at only 66 of the 161 stations sampled on mapped reefs, and the overall average live oyster density at those stations was only 17 oysters/m^2 (1.5 oysters/ft^2) (Parker 2016).

The cause of the 2012–2013 fishery collapse has been linked to a combination of events. The conclusions of Camp et al. (2015), paraphrased in the following summary, provide a plausible scenario linking five likely contributing factors: 1) low river flow led to increased salinity in Apalachicola Bay for a multiyear period, which caused 2) an increase in oyster parasites, predators, or unknown pathogens, leading to 3) increased oyster mortality, particularly among juveniles, resulting in 4) recruitment failures (over several years) possibly worsened by shell removal by fishing or environmental events, finally leading to 5) collapse of adult oyster populations.

Numerous studies have assessed the role of river discharge in the long-term dynamics of oyster harvest from the bay, confirming the importance of freshwater discharges to the ecology, production, and harvest of oysters but also underscoring the complex nature of the relationship (Wilber 1992, Wang et al. 2008, Oczkowski et al. 2011, Fisch and Pine 2016). Unfortunately, sufficient data to fully support factors 2 and 3 are not available because studies of predators were not under way before the collapse. But, very high densities of boring sponges and predators have been observed in the bay since the collapse (Fig. 3.7, Camp et al. 2015). Camp et al. (2015; also see Fisch and Pine 2016) also discuss research that arrived at similar explanations for previous fishery collapses in Apalachicola Bay and other parts of the state. Fisch and Pine (2016) did not find a significant correlation between oyster CPUE and river discharge between 1987 and 2013; they posit that this lack of a relationship may be a result of the changes in fishery landings reporting requirements, a lack of a proportional relationship between CPUE and oyster populations, hurricane impacts, and changes to ecosystem dynamics in the bay. Overfishing is not thought to have directly contributed to the 2012 collapse, in the sense that recruitment was not limited by harvest (FWC 2013, Pine et al. 2015). Rather, the fishery may have indirectly exacerbated the collapse through the removal of shell substrate (Camp et al. 2015, Pine et al. 2015).

The fishery collapse resulted in a request by the State of Florida for a Federal Fisheries Disaster declaration. The request was granted in 2013 by the U.S. Secretary of Commerce, enabling the use of federal funds to support the community in the aftermath of the collapse (Havens et al. 2013). These funds, as well as funding from the Florida Department of Economic Opportunity, led to the Apalachicola Bay Fishery Disaster Recovery Project Plan, which included restoration of oyster habitat, monitoring of oyster resources and restoration efforts, vocational and educational training for affected oyster fishers and their communities, and processor facilities

Figure 3.7. An abundance of oyster drills (*Stramonita haemastoma*) and their egg cases on a concrete block left for one month to monitor oyster spat settlement in Apalachicola Bay in 2018 (photo credit: Nicole Martin).

upgrades. Several studies were also published focusing on various aspects of the ecological and social dimensions of the collapse. Fisch and Pine (2016) focused on the complexities of the relationship between freshwater discharge and oyster landings. Camp et al. (2015) and Pine et al. (2015) explored the relationship between ecological and social issues, focusing on management strategies that should be considered to enhance resiliency in the fishery. Kimbro et al. (2017) and Pusack et al. (2018) demonstrated the potential importance of predation as related to freshwater discharges to the bay in oyster population dynamics. Overall, recent research has provided new perspectives on the temporal and spatial dynamics of oyster populations in Apalachicola Bay, as well as the complexity and importance of the fishery to the regional economy and local communities.

Legal battles over water rights have been ongoing between the states of Florida, Alabama, and Georgia since the 1980s. But after the 2012–2013 oyster fishery collapse, the State of Florida sought to have the Court apportion water rights in the ACF watershed. The State of Florida argued that Georgia's water policies negatively affected Apalachicola's oyster fishery, resulting in the collapse of the oyster population and the loss of many of the ecosystem services that oysters provide. Florida stated its concern that upstream water use will continue to increase as urban and agricultural demands for water grow in Georgia, inhibiting the recovery of the fishery. In 2014, the U.S. Supreme Court agreed to hear *State of Florida v. State of Georgia* over the appropriation of water from the ACF basin (Fisch and Pine 2016). In 2017, the court-appointed special master recommended that the court side with Georgia because Florida had failed to prove that a water-consumption cap would have averted the fishery collapse (Lancaster 2017). In June 2018, however, the Supreme Court declared that the special master had applied too strict a standard in requiring Florida to prove its case and ordered reconsideration of the case (Florida v. Georgia 2018, Pittman 2018). Review of the case under a new special master is ongoing at the time of the writing of this report.

Little research has dealt with the substantial ecosystem services such as habitat provision, water filtration, and fish production that Apalachicola Bay's oyster reefs

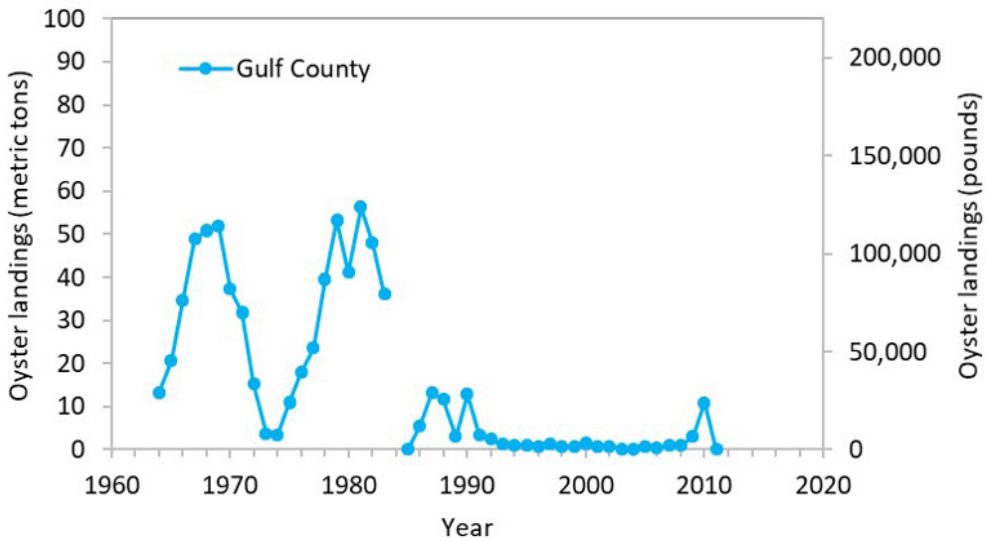

Figure 3.8. Commercial oyster harvest from Gulf County (western Apalachicola Bay). Data sources: FWC (2017) and Florida Commercial Marine Fish Landings (see Appendix A).

provide (Coen et al. 2007, Grabowski and Peterson 2007). In addition to oyster landings and economic impacts, the 2012 fishery collapse in the bay also resulted in a loss of some portion of the ecosystem services the oyster reefs provided. The collapse thus had ecological as well as economic and social effects. In their assessment of long-term changes in water filtration by oyster reefs in 13 estuaries in North America, zu Ermgassen et al. (2013) found only Apalachicola Bay showed an increase in filtration capacity. However, their assessment was based on 1990–2010 data, prior to the 2012 collapse (see Table 1 in zu Ermgassen et al. 2013). It is reasonable to assume that other ecosystem services provided by the bay's oyster reefs have also greatly diminished since 2012.

Finally, a recent result of the Apalachicola Bay oyster fishery collapse is that much of the oyster fishery (harvest and management) shifted to the Big Bend region. In 2016, yields from the Big Bend equaled those from Apalachicola Bay (FWC 2018). In 2017, commercial oyster landings for the Big Bend increased to 219 metric tons (483,000 pounds), surpassing the Franklin County yield of 122 metric tons (268,000 pounds; FWC 2018). There has also been a renewal of interest in oyster aquaculture in which oysters are grown in cages suspended in the water column, where they are safer from predators and less vulnerable to sedimentation or hypoxic conditions (Reiley 2018). This shift is similar to changes occurring in other estuaries, where traditional oyster fisheries that have failed or are greatly diminished are being supplemented with aquaculture practices.

Indian Lagoon

Located at the westernmost edge of Apalachicola Bay, Indian Lagoon (Fig. 3.1) is within the borders of Gulf County and is not part of ANERR. The lagoon is bounded by Indian Pass peninsula and opens to St. Vincent Sound to the east and the Gulf of Mexico to the southeast at Indian Pass. The lagoon is shallow with a bottom of fine organic sediments (FDEP 2014), and most oyster reefs in the lagoon are intertidal (Fig. 3.3; Grizzle et al. 2017a). Oysters from Indian Lagoon make up most of the landings from Gulf County, which were at substantial levels during the 1960s and 1980s but have been at record low levels since 1990 (Fig. 3.8).

Eastern Franklin County

Oyster reefs also exist in Alligator Harbor and Ochlockonee Bay in eastern Franklin County (Fig. 3.1). Alligator Harbor is a barrier-spit lagoon partly enclosed by Alligator Point peninsula. It has a mean low water depth of approximately 1.2 m (4 ft) (FDEP 2018). Salinity is similar to that in the Gulf of Mexico due to negligible freshwater input. There are some small areas of dense intertidal and subtidal oyster reef in the eastern end of the Harbor, as well as some scattered larger reefs and oyster growth associated with salt marshes (Fig. 3.1; FDNR 1986, FDEP 2018). Little data, however, are available on the condition of these reefs (FDEP 2018). Clam aquaculture was established in 2002 and off-bottom oyster aquaculture was approved in 2015 on leases in Alligator Harbor Aquatic Preserve. The University of Florida In-

stitute of Food and Agricultural Sciences intermittently monitored water quality near these shellfish harvesting areas from 2002–2012; monitoring was discontinued in 2012 due to lack of funding (FDEP 2018).

Ochlockonee Bay receives freshwater flow from the Ochlockonee River. The watershed of this river covers 6,412 km^2 (2,476 mi^2), including parts of southern Georgia and the city of Tallahassee (NWFWMD 2017). Human population in the watershed is steadily increasing, and with population growth comes concerns for proper wastewater and stormwater management. Ochlockonee Bay includes extensive seagrass beds and coastal salt marshes. Salinity in the bay varies with river flow, and the bay is often stratified (NWFWMD 2017). Salinity has remained sufficiently low in the upper half of the bay to protect oysters there from key predators (Kimbro et al. 2017).

Threats to oysters in Apalachicola Bay

Several recent papers provide a comprehensive analysis of the relationship between the Apalachicola Bay's oyster fishery (and, indirectly, its oyster populations) and various environmental factors, thus providing an overview of threats to oysters (Camp et al. 2015, Pine et al. 2015, Fisch and Pine 2016, Kimbro et al. 2017, Pusack et al. 2018). From those papers, four of the most important factors are described below (and in some cases in sections above).

- **Altered hydrology:** Water withdrawals and other changes in the hydrology of the ACF river system represent a threat to oysters that has been at the center of debate and litigation for decades. A network of dams in the ACF river system alters freshwater flow rates, sediment delivery, and erosion patterns for the Apalachicola River and Bay. When this altered hydrology is coupled with low precipitation and urban and agricultural demand for fresh water, the resulting low freshwater flow and high salinity make oysters more vulnerable to dermo (*Perkinsus marinus*) and predators such as the stone crab (*Menippe mercenaria*) and southern oyster drill (*Stramonita haemastoma*) (Livingston et al. 2000, Kimbro et al. 2017, Pusack et al. 2018). Parasites, such as the boring sponge, boring clam, and polychaetes also cause damage to the oysters' shells, possibly resulting in death. The shells become weakened, leaving the oyster more vulnerable to predators (Havens et al. 2013).
- **Sea-level rise:** The combined impact of decreasing freshwater inflow and rising sea level will likely lead to more frequent instances of high salinity in the region. Even with modest increases in sea level, more saline water will enter the bay through East Pass, which will push river discharge toward the west with tidal currents (Huang et al. 2015). Cat Point is expected to experience greater increases in salinity than Dry Bar, as freshwater flow from Apalachicola River is pushed toward Dry Bar (Huang et al. 2015). While most oysters in Apalachicola Bay are subtidal, intertidal oysters will have to cope with increased submergence times. Solomon et al. (2014) found that shell length and recruitment are greatest at high rates of submergence for intertidal oysters in Apalachicola Bay. However, these submerged reef elevations also had the highest rates of sedimentation, which can smother reefs.
- **Hurricanes and tropical storms:** Hurricanes can negatively impact oysters and may cause erosion of reef substrate, sedimentation and burial of reefs, and extreme salinity changes (Edmiston et al. 2008). Hurricanes also redistribute shell off the reef, where it can be buried and lost in the mud (Twichell et al. 2010). Storms often bring heightened pollutant and nutrient loads with terrestrial runoff, which can feed algal blooms (including red tide) and lead to hypoxia (Edmiston et al. 2008).
- **Harvesting:** The effect of harvest on a fishery is generally considered a threat only if harvest exceeds the ability of the population to replenish itself. Pine et al. (2015) found that Apalachicola Bay was not experiencing recruitment overfishing, whereby the population of adults can no longer replace itself. There is no assessment of growth overfishing, whereby oysters may be harvested at a size too small to support a maximum sustainable yield, but one still might argue that if the number of legal-size oysters were extremely limiting, growth overfishing might be occurring. However, removal of shell substrate can cause impacts similar to overfishing as it results in the loss of substrate. Substrate loss is a significant factor for poor recruitment; therefore, fishing without shell replacement (as well as illegal fishing not complying with regulations) greatly reduces the chance that populations may recover (Havens et al. 2013). The effect of harvest on the ecosystem services oyster reefs provide, however, has not been well assessed and remains controversial (Beck et al. 2011).

Apalachicola Bay oyster mapping and monitoring efforts

Historical oyster mapping

Oyster maps for Apalachicola Bay date to the work of Franklin Swift who conducted a comprehensive survey in 1895–1896 for the U.S. Commission of Fish and Fisheries and published a detailed map based on 75,000 manual sounding points (Swift 1897). This map represents the

Figure 3.9. Composite map of the surficial geology of Apalachicola Bay based on 2005–2006 sonar-based mapping. (Figure from Twichell et al. 2007.)

modern starting point for the knowledge of the distribution of natural reefs in the bay before the extensive shell planting programs discussed above were started.

U.S. Geological Survey geophysical mapping of subtidal oysters

Following Swift (1897), another comprehensive survey of Apalachicola's subtidal reefs did not occur until 2005–2006, when the U.S. Geological Survey used interferometric multibeam bathymetry, side-scan sonar, and seismic-reflection techniques to create detailed maps of oyster reefs (Fig. 3.9; Twichell et al. 2007). Data were collected using an outboard-propelled boat, which was used to survey depths greater than 2 m (6.5 ft); an autonomous surface vehicle was used to survey depths between 0.75 and 2 m (2.5–6.5 ft). Approximately one-third of the total bottom area of the bay was not surveyed due to very shallow or very deep water, and they did not survey St. Vincent Sound. This effort characterized the relationship between current oyster reefs, bay floor morphology, and how the reefs likely developed in the long term (Twichell et al. 2010; see discussion in Ecology section above). Shapefiles from these surveys are available for download at https://catalog.data.gov/dataset/benthic-habitats-and-surficial-geology-of-apalachicola-bay-florida-2006-geodatabase.

FDACS compilation

The FDACS Division of Aquaculture compiled mapping data from Twichell et al. (2007) with information on shelling locations (Fig. 3.10). The reefs shown on the FDACS map are mainly subtidal, though some nearshore reefs are likely intertidal. This map is likely the most comprehensive map that differentiates between natural and constructed (restored) oyster reefs in the bay. It should be noted that the FDACS compilation and Twichell et al. (2007) focus on subtidal oyster reefs (Figs. 3.9–3.10) and provide only spatial data; i.e. no information on oyster reef condition is indicated or implied.

Intertidal reef mapping by the University of New Hampshire and The Nature Conservancy

Oyster reefs in the intertidal areas of Apalachicola Bay have largely been neglected in most mapping efforts because most of the oyster harvest has come from subtidal reefs, and the area covered by intertidal reefs is much less than by subtidal reefs. The University of New Hampshire (UNH) and The Nature Conservancy (TNC) developed new maps for oyster reefs in Apalachicola Bay and assessed the potential of high-resolution satellite imagery for mapping and monitoring (Grizzle et al. 2017a). The

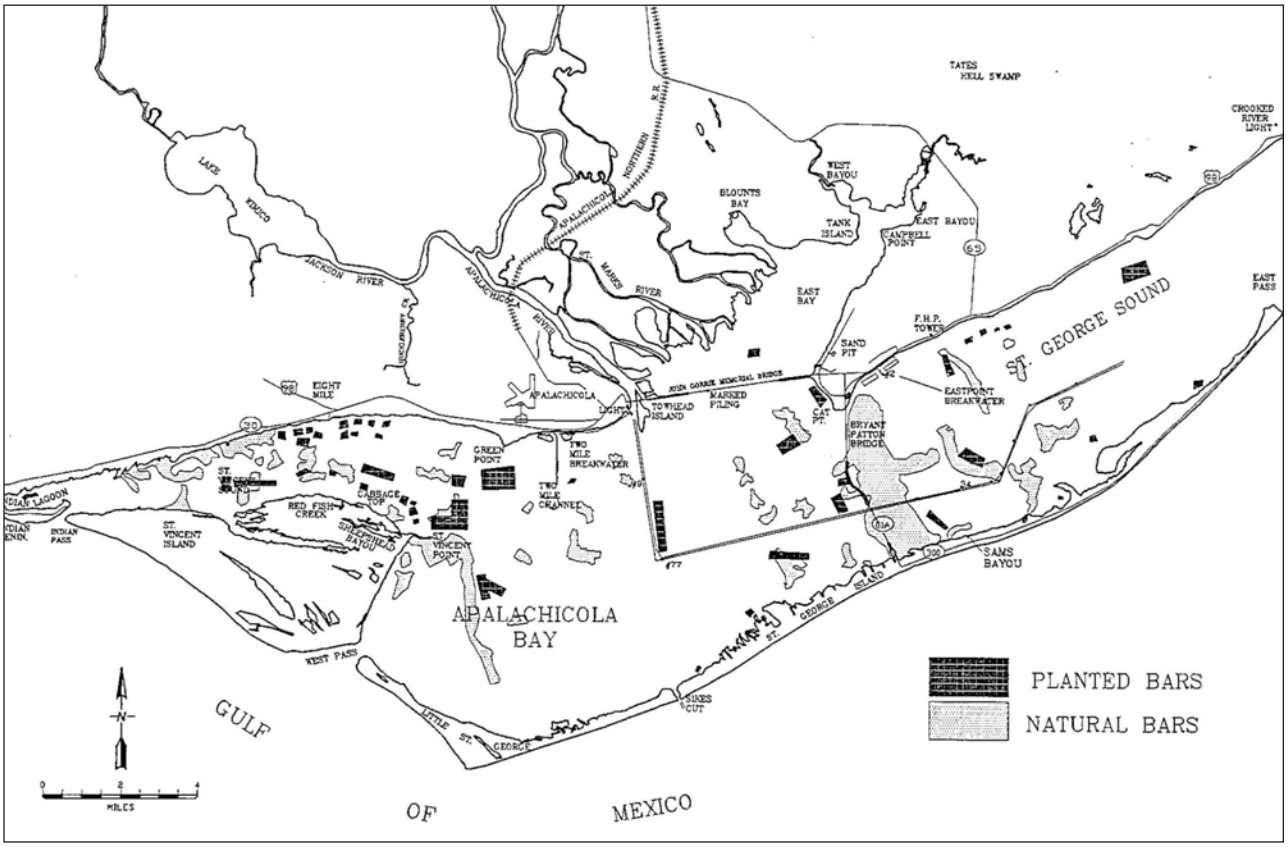

Figure 3.10. Composite map from FDACS' Division of Aquaculture showing oyster bottom areas (planted and natural bars) in Apalachicola Bay (provided by Joe Shields).

project used both high-resolution GeoEye satellite imagery from Grizzle et al. (2015) and ground truthing to assess the position and size of oyster reefs at the time. One hundred reefs were sampled, and oyster density was analyzed. This study concluded that most of the oyster reefs on the western side of the bay consisted of dead shells, indicative of a recent mass mortality, with little recent recruitment. Comparison of ground-truthing data to satellite imagery indicated a classification accuracy of 77–97%. A total of 777 reefs were mapped, covering 78.5 ha (194 ac) of bay bottom.

Figure 3.11 is a composite map that combines most of the data from previously published subtidal maps mentioned above with the intertidal oyster reefs mapped by Grizzle et al. 2017a. This compilation and the FWC compilation (Fig. 3.1 and discussed below) represent the most comprehensive maps available showing the shape, size, and location of the major oyster reefs in Apalachicola Bay. No spatially detailed data are available on the condition of these reefs apart from the intertidal reefs mapped by the University of Central Florida (UCF) and UNH (see data in Grizzle et al. 2016, 2017a, 2017b).

Intertidal reef mapping by the University of Central Florida

Researchers from UCF (Melinda Donnelly, Linda Walters, Stephanie Garvis, and Joshua Solomon) used Landsat imagery from 2012 (USGS) of Apalachicola Bay to map locations of intertidal oyster reefs. After initial mapping, ground truthing was used to evaluate the accuracy of the imagery interpretation. Field observations were conducted at a total of 100 random locations (50 oyster, 50 nonoyster) in summer 2013 (96% accuracy). A total of 603 intertidal reefs were identified, covering approximately 80 ha (198 ac); the majority of intertidal reefs were found near natural shorelines on lands managed by St. George Island State Park and St. Vincent National Wildlife Refuge. Mapping was supported by a grant from NOAA. Shapefiles are available by contacting Melinda Donnelly (Melinda.Donnelly@ucf.edu).

Northwest Florida Water Management District oyster mapping

The most recent NWFWMD land-use/land-cover (LULC) map that included a separate oyster reef layer is

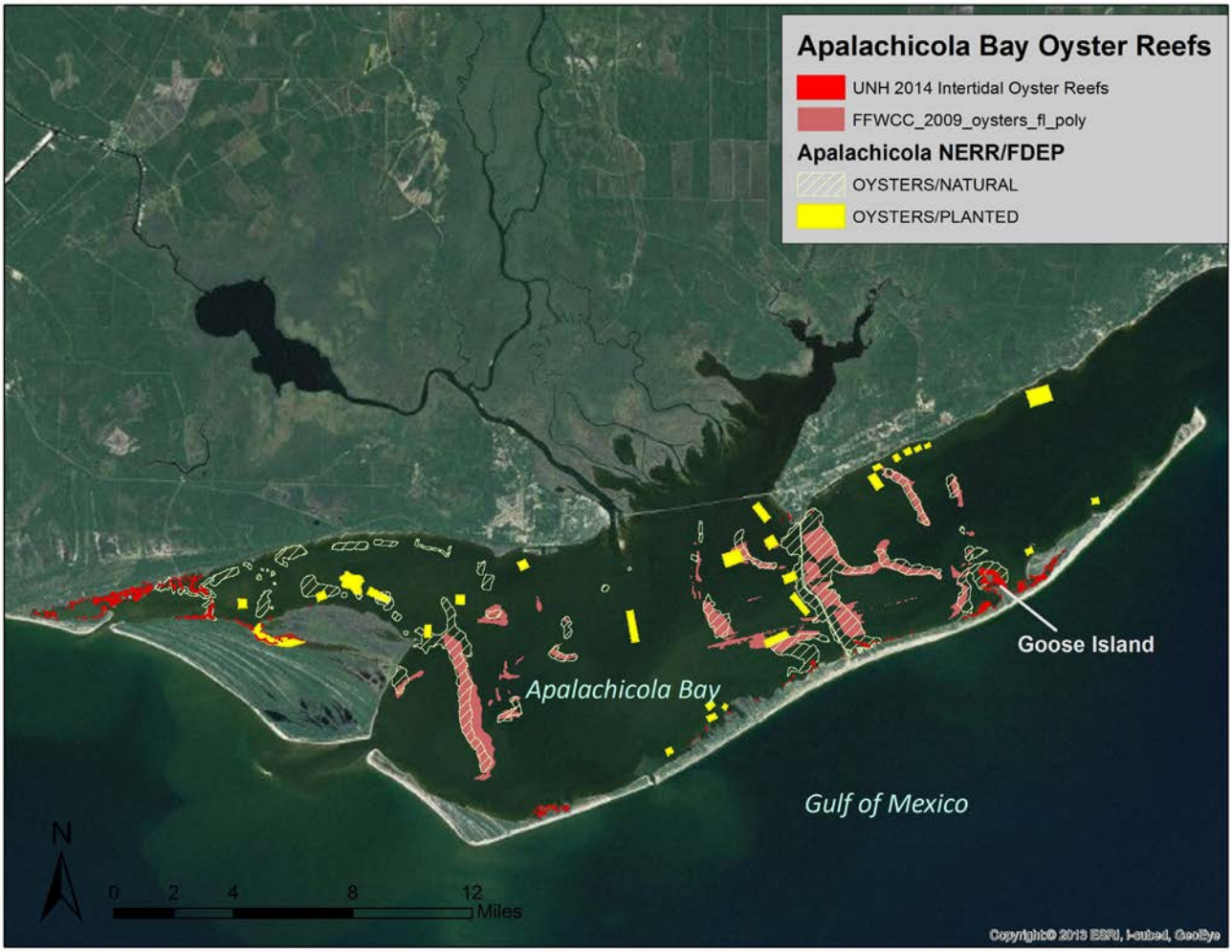

Figure 3.11. Composite map of intertidal and subtidal oyster reefs. UNH 2014 intertidal oyster reefs were mapped using 2012 satellite imagery (Grizzle et al. 2015, Grizzle et al. 2017a); FFWCC (FWC) 2009 layer compiled data from Twichell (2007) and historical data; Apalachicola NERR/FDEP data set from 2007 and 2010 aerial photographs and historical data sets (ANERR 2013). Figure from Grizzle 2017a.

from 2009–2010 (NWFWMD 2010). Oysters were mapped following the Florida Land Use and Cover Classification System (FLUCCS), which included a category for oyster bars (FLUCCS 6540; FDOT 1999). Mapped oyster reefs in Gulf and Franklin counties included intertidal oysters in Indian Lagoon, Alligator Harbor, and Ochlockonee Bay (Fig 3.1). While NWFWMD LULC maps from 2012–2013 are available, oyster bars were not mapped in those years. NWFWMD shapefiles are available for download at http://www.fgdl.org/metadataexplorer/explorer.jsp.

Apalachicola National Estuarine Research Reserve mapping and monitoring

ANERR mapped land cover and benthic cover in the reserve using high-resolution imagery from 2007 and 2010 (ANERR 2013). The minimum mapping unit was 0.02 ha (0.05 ac). Subtidal oyster reef extent was compiled by Twichell et al. (2007), and a lower-resolution data set of benthic communities was compiled using infrared photographs by the GIS group at FWC's Florida Marine Research Institute (since renamed Fish and Wildlife Research Institute) (FWC 1986). The ANERR shapefile is available for download at http://cdmo.baruch.sc.edu/get/gis.cfm.

Monitoring within ANERR includes its System-Wide Monitoring Program, which began in 1992 and monitors water quality at Cat Point, East Bay, and Dry Bar to study the effects of changing river flow on the environmental variables at those sites. More water quality stations were added at Pilot's Cove in 2015 and at Little St. Marks in 2016. Since 2002, monthly sampling for nutrient and chlorophyll-*a* began including sites throughout the bay, Apalachicola River, and offshore. ANERR also has a

weather station that has collected meteorological data in East Bay since 1999. All data are available at http://cdmo.baruch.sc.edu/.

ANERR has also collaborated with multiple researchers for large-scale studies of oyster populations in relation to physical parameters within Apalachicola Bay. Petes et al. (2012) looked at oyster mortality in relation to salinity, temperature, and presence of dermo. They found that oysters suffered more disease-related mortality in high-salinity conditions, especially during warmer months, and that vulnerability was size specific; larger oysters were more susceptible. Kimbro et al. (2017) studied the effects of salinity on predation rates by the oyster drill on oysters in Apalachicola Bay; Pusack et al. (2018) further studied the impacts of predator density on predation rates.

FWC oyster map compilation

FWC has compiled many of the maps described above to create a comprehensive oyster map for Apalachicola Bay (compilation map shown in Fig. 3.1). Data sets include those from FWC (1986), Twichell (2007), NWFWMD (2010), ANERR (2013), and Grizzle (2017a). The compilation is available for download at http://geodata.myfwc.com/datasets/oyster-beds-in-florida.

Apalachicola Bay restoration mapping and monitoring

An oyster cultch placement project in Franklin County was funded by a Gulf Coast Ecosystem Restoration Council grant (GCERC 2016). This project is a continuation of a Deepwater Horizon Natural Resource Damage Assessment (NRDA) Phase III Early Restoration project and National Fish and Wildlife Foundation project. The project involved the placement of suitable cultch on depleted oyster reefs to promote new oyster colonization. The coordinates and description of these restoration efforts can be found in the project report (FDACS 2017b). Approximately 72,000 m^3 (95,000 yd^3) of lime rock aggregate were deposited onto an estimated 128 ha (317 ac) of depleted reefs in the fall of 2017. Site selection and cultch placement were coordinated through FDACS. FDEP's Central Panhandle Aquatic Preserves office is monitoring the success of this restoration effort. Cultched reefs will be mapped in the Apalachicola Bay system to depict the extent of enhanced oyster reefs.

A second cultch restoration project focused in Apalachicola Bay was initiated in 2014 and is also funded by oil spill reparation funding through the National Fish and Wildlife Foundation. This ongoing five-year project is a collaboration between FWC, the University of Florida (UF), FDACS, and UNH. The initial component of the project was overseen by FDACS and involved the placement of fossil shell at three experimental sites in Apalachicola Bay. At each of those experimental sites, five 2-ac parcels were delineated and cultched at different shell densities (0, 100, 200, 300, and 400 yd^3/ac) in order to identify optimal shell density for future restoration efforts. Following construction, UNH and Substructure Inc. conducted acoustic mapping and ground truthing of the experimental sites. FWC and UF are monitoring oyster density, size distribution, and oyster health and condition assessments. The coordinates and description of cultching efforts can be found in FDACS's final report summarizing its component of the project (FDACS 2015b). Details and results from the acoustic mapping component can be found in UNH's final report (Grizzle et al. 2017b).

Fishery disaster recovery project

Ongoing efforts for the recovery of Apalachicola Bay following the collapse of the oyster fishery in 2012–2013 are collaborative between the Florida Department of Economic Opportunity, FDACS, FDEP, and FWC. The ongoing monitoring component is conducted by FWC and includes pre– and post–commercial season metrics of oyster density at 15 oyster reefs located throughout the bay. In addition, monthly measures of larval settlement rates are recorded at those same reefs. The monitoring component also included a fishery-independent survey of oysters throughout Apalachicola Bay (mentioned in the Ecology section). Survey locations were randomly selected from areas deemed likely oyster habitat based on shapefiles and data sets. A total of 161 stations were sampled, and results indicate that many areas considered potential oyster habitat have experienced substantial loss of settlement substrate (Parker 2016).

FWC oyster population monitoring

In July 2015, the State of Florida provided funding for the establishment an annual monitoring program for Apalachicola's commercially fished oyster reefs for fishery management purposes. This program continues the annual oyster density and size monitoring that had been conducted by FDACS since 1990. In addition, the FWC program conducts monthly measures of oyster condition, dermo prevalence and intensity, reproductive development, and incidence and severity of shell pest infestations. The FWC program will continue to monitor monthly lar-

val settlement rates after the Fishery Disaster Recovery Project concludes in 2019.

Modeling efforts in Apalachicola Bay

A series of papers has been published concerning the modeling of multiple abiotic parameters in Apalachicola Bay. Several directly relate their findings to the oyster population. Models include oyster population as a function of freshwater input (Livingston et al. 2000), wind effects on salinity (Huang et al. 2002), impacts of sea-level rise on salinity (Huang et al. 2014), oyster growth rate as a function of hydrodynamic models (Wang et al. 2008), and impacts of sea-level rise on salinity and oyster growth (Huang et al. 2015). Singh et al. (2015) modeled the impact of climate variability on baseline flow within the ACF river basin.

Environmental Sensitivity Index maps

Environmental Sensitivity Index (ESI) maps depict coastal zone natural resources. These maps are designed for use in damage evaluation, prevention, and clean-up for oil spills. Areas are mapped on a scale of sensitivity based on potential exposure, biological productivity, and ease of cleanup. ESI maps depict the locations of oysters and several other shellfish species in low, medium, and high concentrations. These concentration categories are subjective and based on the opinion of local experts. Oyster mapping data for northwest Florida was published in 1995 (RPI 1995). More information and ESI mapping data can be found at http://ocean.floridamarine.org/esimaps/.

Disease monitoring

The prevalence and intensity of dermo in the eastern oyster are monitored in several locations in Apalachicola Bay by the Oyster Sentinel, established by Thomas Soniat at the University of New Orleans. Monitoring locations and data are available at http://www.oystersentinel.org. Monitoring includes water temperature and salinity.

Contaminant monitoring

Oyster samples from Cat Point Bar and Dry Bar in Apalachicola Bay are included in the National Oceanic and Atmospheric Administration's (NOAA's) Mussel Watch program, which monitors sites around the United States for organic and inorganic pollutants. Oysters from Apalachicola Bay had moderate levels of arsenic and mercury (Kimbrough et al. 2008).

Recommendations for mapping, monitoring and management

- Design and implement periodic and extensive mapping of subtidal and intertidal reefs that is both practical and sustainable. While portions of intertidal reefs have recently been mapped and characterized, there has been no comprehensive mapping of the bay's entire subtidal oyster reef system since Swift (1897). Such a program should yield data that can be coupled with fishery-independent monitoring of the condition of the reefs in all areas of the bay to more fully assess the bay's oyster resources.
- Monitor the condition of the bay's oyster reefs, including harvested and nonharvested reefs. Fishery-dependent data are limited to reefs open to fishing, so fishery-independent monitoring should be expanded to include adequate sampling of both harvested and non-harvested reefs (Havens et al. 2013). The resulting data should be coupled with mapping programs to improve understanding of spatial and ecological relationships between the bay's oyster reefs and environmental variability.
- Better manage the fate of oyster shell removed during harvest. The importance of adequate hard substrate for larval settlement, and thus long-term sustainability of oyster reefs, has long been recognized (Swift 1898). Shelling programs have been conducted in Florida by FDACS, but no permanent funding source exists. These programs have focused on Apalachicola Bay and, more recently but to a lesser extent, St. Andrew and Pensacola bays, but they have relied on grants. The importance of shelling programs to oyster management is well established (Pine et al. 2015). Many questions remain, however, with respect to details in program design (Havens et al. 2013). Ongoing research is aimed at assessing optimal densities for deployment of fossil shell, but research also is needed on where shell plantings should be located, the types of substrate (e.g., fossil shell, recycled seasoned shell) that are most effective, and how to spread the shell.
- Investigate management needs and social issues related to salinity and river discharge requirements for Apalachicola Bay. Increased salinity as a result of reduced river discharges to the bay and sea-level rise is a major threat to oysters in this region, but also one of the most difficult to address. Litigation continues for water rights between states in the ACF watershed (Florida v. Georgia 2018, Pittman 2018). Although there has been a substantial amount of research on how oyster popu-

lations respond to increasing salinity, including research in Apalachicola Bay, research is also needed on how to address such complicated social issues from a management perspective.

- Continue research on the ecological roles of oysters in Apalachicola Bay. The bay's oyster resource has historically been managed almost entirely as a resource for human harvest, but oyster reefs also provide habitat, improve water quality through filter feeding, and are components of the estuary food chain. More information is needed particularly on how oyster harvest practices impact these ecological roles, and on how to optimize ecosystem functionality in a heavily harvested estuary.
- Further explore the role of oyster aquaculture in the bay. Oyster farming and oyster fishing are not mutually exclusive, but the tradition in Apalachicola Bay has not included aquaculture. In contrast, oyster farming is becoming increasingly common in other Florida estuaries, such as nearby Apalachee Bay and Alligator Harbor (FDEP 2018; Reiley 2018). The use of Territorial User Rights Fisheries (TURFs; Prince et al. 1998), in which oysters are harvested from areas leased to individual oyster farmers rather than from common-use public reefs (Havens et al. 2013, Camp et al. 2015), should also be explored. Individual leases help prevent unsustainable fishing practices and shell removal and encourage stewardship of reefs for long-term use, such as shelling to replace lost substrate.
- Involve all relevant state agencies, experts from academic institutions, and community organizations such as the Seafood Management Assistance Resource and Recovery Team (SMARRT) to develop an oyster management plan for the long-term well-being of oyster populations and the oyster industry in Apalachicola Bay. Although the present oyster shell height limit of 76 mm (3 in) is appropriate, it needs to be better enforced. Harvesting sublegal-size oysters is detrimental to future Apalachicola Bay oyster populations (Havens et al. 2013). Spatial restrictions and temporary closures need to be enforced and respected, including continuation or implementation of on-land and on-water checks. A bag tax used to fund research and monitoring programs that ended in the 1990s could also be reinstated (Pine et al. 2015).
- Enhance community outreach with partnerships in research, policy development, and education. The most effective policies will be those that result from a broad support base and are responsive to changes and new knowledge.

Works cited

ANERR (Apalachicola National Estuarine Research Reserve). 2013. High-resolution land cover Apalachicola Bay NERR. Available from http://cdmo.baruch.sc.edu/get/gis.cfm, accessed March 2018.

Beck MW, Brumbaugh RD, Airoldi L, Carranza A, et al. 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. BioScience 61:107–116.

Berrigan ME. 1988. Management of oyster resources in Apalachicola Bay following Hurricane Elena. Journal of Shellfish Research 7:281–288.

Berrigan ME. 1990. Biological and economical assessment of an oyster resource development project in Apalachicola Bay, Florida. Journal of Shellfish Research 9:149–158.

Camp EV, Pine WE III, Havens K, Kane AS, et al. 2015. Collapse of a historic oyster fishery: diagnosing causes and identifying paths toward increased resilience. Ecology and Society 20:45.

Coen LD, Brumbaugh RD, Bushek D, Grizzle R, et al. 2007. Ecosystem services related to oyster restoration. Marine Ecology Progress Series 341:303–307.

Dugas RJ, Joyce EA, Berrigan ME. 1997. History and status of the oyster, *Crassostrea virginica*, and other molluscan fisheries of the U.S. Gulf of Mexico. MacKenzie CL, Burrell Jr. VG, Rosenfield A, Hobart WL, editors. In: The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. Volume 1. Atlantic and Gulf Coasts. Washington, DC: NOAA, U.S. Department of Commerce. Technical Report NMFS 127. p. 187–210.

Edmiston, HL. 2008. A river meets the bay, a characterization of the Apalachicola River and Bay system. Apalachicola, FL: Apalachicola National Estuarine Research Reserve, Florida Department of Environmental Protection. Available from https://coast.noaa.gov/data/docs/nerrs/Reserves_APA_SiteProfile.pdf.

Edmiston HL, Fahrny SA, Lamb MS, Levi LK, et al. 2008. Tropical storm and hurricane impacts on a Gulf coast estuary: Apalachicola Bay, Florida. Journal of Coastal Research 55:39–48.

Fisch NC, Pine WE III. 2016. A complex relationship between freshwater discharge and oyster fishery catch per unit effort in Apalachicola Bay, Florida: An evaluation from 1960 to 2013. Journal of Shellfish Research 35:809–825.

FDACS (Florida Department of Agriculture and Consumer Services). 2015a. Natural Resources Damage Assessment: oyster reef restoration in Apalachicola

Bay: Purchase and placement of oyster cultch material. Tallahassee, FL: Division of Aquaculture, FDACS.

FDACS (Florida Department of Agriculture and Consumer Services). 2015b. Apalachicola Bay Oyster Restoration (FL), NFWF Shell Planting Density Study. Tallahassee, FL: FDACS. National Fish and Wildlife Foundation Grant.

FDACS (Florida Department of Agriculture and Consumer Services). 2017a. Shellfish harvest area classification. Available from http://www.freshfromflorida.com/Business-Services/Aquaculture/Shellfish-Harvesting-Area-Classification/Shellfish-Harvesting-Area-Maps, accessed December 2017.

FDACS (Florida Department of Agriculture and Consumer Services). 2017b. Gulf Coast Ecosystem Restoration Council grant, oyster reef restoration in the Apalachicola Bay system, oyster cultch deposition. Tallahassee, FL. Available from http://www.gulfspillrestoration.noaa.gov/florida-oyster-cultch-placement-project, accessed July 2018.

FDEP (Florida Department of Environmental Protection). 2014. Apalachicola National Estuarine Research Reserve Management Plan. Tallahassee, FL: Coastal and Aquatic Managed Areas, FDEP. Available from http://publicfiles.dep.state.fl.us/cama/plans/aquatic/ANERR-Management-Plan-2013.pdf.

FDEP (Florida Department of Environmental Protection). 2018. Alligator Harbor Aquatic Preserve Management Plan. Tallahassee, FL: Office of Coastal and Aquatic Managed Areas, FDEP. Available from http://publicfiles.dep.state.fl.us/CAMA/plans/aquatic/Alligator-Harbor-AP-Management-Plan.pdf.

FDNR (Florida Department of Natural Resources). 1986. Alligator Harbor Aquatic Preserve Management Plan. Tallahassee, FL: FDNR.

FDOT (Florida Department of Transportation). 1999. Florida land use, cover and forms classification system, 3rd edition. Tallahassee, FL: State Topographic Bureau, Thematic Mapping Section. Available from https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/content/geospatial/documentsandpubs/fluccmanual1999.pdf?sfvrsn=9881b4d0_0, accessed April 2017.

FWC (Florida Fish and Wildlife Conservation Commission). 1986. Benthic habitat of Apalachicola Bay, Florida: historic [map]. St. Petersburg, FL: Florida Marine Research Institute.

FWC (Florida Fish and Wildlife Conservation Commission). 2013. 2012–2013 Florida Gulf coast oyster disaster report. Tallahassee, FL: FWC. Available from http://www.floridajobs.org/docs/default-source/2015-community-development/2015-cmty-plan-acsc/20122013floridagulfcoastoysterdisasterreport.pdf.

FWC (Florida Fish and Wildlife Conservation Commission). 2018. Commercial Fisheries Landings in Florida. St. Petersburg, FL: Fish and Wildlife Research Institute. Available from http://myfwc.com/research/saltwater/fishstats/commercial-fisheries/landings-in-florida/, accessed November 2018.

Florida v. Georgia. 2018. Supreme Court of the United States, Syllabus: Florida v. Georgia on exceptions to the report of special master. October Term 2017. No. 142, argued January 8, 2018—Decided June 27, 2018. Available from https://www.supremecourt.gov/opinions/17pdf/142%20orig_h3ci.pdf.

Grabowski JH, Peterson CH. 2007. Restoring oyster reefs to recover ecosystem services. Cuddington K, Byers JE, Wilson WG, Hastings A, editors. In: Ecosystem engineers: concepts, theory and applications. Amsterdam, Netherlands: Elsevier-Academic Press. p. 281–298.

Grabowski JH, Powers SP, Roman H, Rouhani S. 2017. Potential impacts of the 2010 Deepwater Horizon oil spill on subtidal oysters in the Gulf of Mexico. Marine Ecology Progress Series 576:163–174.

Grizzle RE, Ward KW, Pine W III. 2015. Apalachicola Bay Florida oyster habitat mapping and characterization pilot project. Maitland, FL: The Nature Conservancy. Final report.

Grizzle R, Ward K, Geselbracht L, Birch A. 2017a. Apalachicola Bay Florida intertidal oyster (*Crassostrea virginica*) reef mapping and characterization. Tallahassee, FL: Final Report to the Florida State Wildlife Grants Program by the University of New Hampshire and The Nature Conservancy. Available from https://f50006a.eos-intl.net/ELIBSQL12_F50006A_Documents/Geselbracht%20June%202017.pdf.

Grizzle R, Ward K, Waddington T. 2017b. Mapping and characterizing restored oyster habitat in Apalachicola Bay Florida. St. Petersburg, FL: Fish and Wildlife Research Institute, FWC. Final report. Available from https://f50006a.eos-intl.net/F50006A/OPAC/Details/Record.aspx?BibCode=5082667.

GCERC (Gulf Coast Ecosystem Restoration Council). 2016. Comprehensive plan update 2016: restoring the Gulf coast's ecosystem and economy. Tallahassee, FL: GCERC, Department of Agriculture. Available from https://www.restorethegulf.gov/sites/default/files/CO-PL_20161208_CompPlanUpdate_English.pdf.

Havens K, Allen M, Camp E, Irani T, et al. 2013. Apalachicola Bay oyster situation. Gainesville, FL: Institute of Food and Agricultural Sciences, University of Florida, Florida Sea Grant Program. Report No. TP-200. Available from https://www.flseagrant.org/wp-content/uploads/tp200_apalachicola_oyster_situation_report.pdf.

Hine AC, Belknap DF, Hutton JG, Osking EB, Evans MW. 1988. Recent geological history and modern sedimentary processes along an incipient, low-energy, epicontinental-sea coastline: Northwest Florida. Journal of Sedimentary Petrology 58:567–579.

Huang W. 2010. Hydrodynamic modeling and ecohydrological analysis of river inflow effects on Apalachicola Bay, Florida, USA. Estuarine, Coastal and Shelf Science 86:526–534.

Huang W, Hagen SC, Bacopoulos P, Teng F. 2014. Sea-level rise effects on hurricane-induced salinity transport in Apalachicola Bay. Journal of Coastal Research 68:49–56.

Huang W, Hagen S, Bacopoulos P, Wang D. 2015. Hydrodynamic modeling and analysis of sea-level rise impacts on salinity for oyster growth in Apalachicola Bay, Florida. Estuarine, Coastal and Shelf Science 156:7–18.

Huang W, Jones K, Wu T. 2002. Modeling surface wind effects on subtidal salinity in Apalachicola Bay. Journal of Estuarine and Coastal Shelf Science 55:33–46.

Ingle RM, Dawson Jr CE. 1953. A survey of Apalachicola Bay, Florida. St. Petersburg, FL: Florida State Board of Conservation. Technical Series 10.

Kennedy V, Sanford LP. 1989. Characteristics of relatively unexploited beds of the eastern oyster, *Crassostrea virginica*, and early restoration programs. Luckenbach MW, Mann R, Wesson JA, editors. In: Oyster reef habitat restoration: a synopsis and synthesis of approaches [proceedings from a symposium]. Williamsburg, VA: Virginia Institute of Marine Science, College of William and Mary. p. 25–46.

Kimbro DL. 2013. Developing cost-effective monitoring for the oyster fishery and an experimental assessment of predator impacts. Havens K, editor. In: Apalachicola Bay oyster situation. Gainesville, FL: Institute of Food and Agricultural Sciences, University of Florida, Florida Sea Grant Program. Report No. TP-200. p. 23–25. Available from https://www.flseagrant.org/wp-content/uploads/tp200_apalachicola_oyster_situation_report.pdf.

Kimbro DL, White JW, Tillotson H, Cox N, et al. 2017. Local and regional stressors interact to drive a salinization-induced outbreak of predators on oyster reefs. Ecosphere 8:1–15.

Kimbrough KL, Johnson WE, Lauenstein GG, Christensen JD, Apeti DA. 2008. An assessment of two decades of contaminant monitoring in the nation's coastal zone. Silver Spring, MD: NOAA. NOAA Technical Memorandum NOS NCCOS 74. Available from https://repository.library.noaa.gov/view/noaa/2499, accessed May 2017.

la Cecilia D, Toffolon M, Woodcock CE, Fagherazzi S. 2016. Interactions between river stage and wetland vegetation detected with a Seasonality Index derived from LANDSAT images in the Apalachicola delta, Florida. Advances in Water Resources 89:10–23.

Lancaster RI Jr. 2017. State of Florida v. State of Georgia Report of the special master. Available from https://www.scotusblog.com/wp-content/uploads/2017/09/2017.02.14-Report-of-Special-Master.pdf.

Livingston RJ. 1984. The Ecology of the Apalachicola Bay System: An Estuarine Profile. Washington, DC: National Coastal Ecosystems Team, Division of Biological Services, U.S. Fish and Wildlife Service. Available from http://npshistory.com/publications/usfws/biological-reports/82-05.pdf.

Livingston, RJ. 2015. Climate change and coastal ecosystems, long-term effects of climate change and nutrient loading on trophic organization. Boca Raton, FL: CRC Press.

Livingston RJ, Howell RL, Niu X, Lewis FG, Woodsum GC. 1999. Recovery of oyster reefs in a Gulf estuary following disturbance by two hurricanes. Bulletin of Marine Science 64:465–483.

Livingston R, Lewis G, Woodsum G, Niu X, et al. 2000. Modeling oyster response to variation in freshwater input. Estuarine, Coastal and Shelf Science 50:655–672.

NERRS (National Estuarine Research Reserve System). 2007. NERRS Centralized Data Management Office GIS application. Georgetown, SC: Office of Coastal Zone Management, NOAA. Available from http://cdmo.baruch.sc.edu/get/gis.cfm, accessed April 2017.

NWFWMD (Northwest Florida Water Management District). 2010. Northwest Florida Water Management District Land Use Land Cover 2009–2010. Havana, FL: NWFWMD. Available from https://www.fgdl.org/metadataexplorer/explorer.jsp, accessed June 2017.

NWFWMD (Northwest Florida Water Management District). 2017. Ochlockonee River and Bay watershed. Surface Water Improvement and Management Plan. Havana, FL: NWFWMD. Program Develop-

ment Series 17-02. Available from https://www.nwfwater.com/Water-Resources/Surface-Water-Improvement-and-Management/Ochlockonee-River-and-Bay, accessed May 2018

Oczkowski AJ, Lewis FG, Nixon SW, Edmiston HL, et al. 2011. Fresh water inflow and oyster productivity in Apalachicola Bay, FL (USA). Estuaries and Coasts 34:993–1005.

Parker, ML. 2016. Apalachicola Bay Fishery Disaster Recovery Project Plan–Job 3. Tallahassee, FL: Florida Department of Economic Opportunity. Oyster Monitoring. Status Report #4.

Petes LE, Brown AJ, Knight CR. 2012. Impacts of upstream drought and water withdrawals on the health and survival of downstream estuarine oyster populations. Ecology and Evolution 2:1712–1724.

Pine WE III, Walters CJ, Camp EV, Bouchillon R, et al. 2015. The curious case of eastern oyster *Crassostrea virginica* stock status in Apalachicola Bay, Florida. Ecology and Society 20:46.

Pittman C. 2018. Supreme Court finally rules on Florida's 30-year water war with Georgia. And it's not over. Tampa Bay Times June 27, 2018. Available from http://www.tampabay.com/news/environment/Supreme-Court-finally-rules-on-Florida-s-30-year-water-war-with-Georgia-And-it-s-not-over-_169506140, accessed July 2018.

Prince J, Walters C, Ruiz-Avila R, Sluczanowski P. 1998. Territorial user's rights and the Australian abalone (*Haliotis* sp.) fishery. Jamieson GS, Campbell A, editors. In: Proceedings of the North Pacific symposium on invertebrate stock assessment and management. Canadian Special Publication of Fisheries and Aquatic Sciences 125. Ottawa, Ontario, Canada: National Research Council of Canada. p. 367–376.

Pusack T, White JW, Tillotson HG, Kimbro DL, Stallings CD. 2018. Size-dependent predation and intraspecific inhibition of an estuarine snail feeding on oysters. Journal of Experimental Marine Biology and Ecology 501:74–82.

Reiley L. 2018. Shell game. Tampa Bay Times, April 11, 2018. Available from http://www.tampabay.com/projects/2018/special-report/shell-game/panhandle-apalachicola-wild-oysters-aquaculture/, accessed April 2018

RPI (Research Planning, Inc). 1995. Sensitivity of coastal environments and wildlife to spilled oil. West Florida Atlas. Tallahassee, FL: Department of Environmental Protection. Available from http://ocean.floridamarine.org/esimaps/pdf/Panhandl/INDEX.pdf.

Shumway SE. 1996. Natural environmental factors. Kennedy VS, Newell RIE, AF Eble, editors. In: The eastern oyster: *Crassostrea virginica*. College Park, MD: Maryland Sea Grant College. p. 467–513.

Singh S, Srivastava P, Abebe A, Mitra S. 2015. Baseflow response to climate variability induced droughts in the Apalachicola–Chattahoochee–Flint River Basin, USA. Journal of Hydrology 528:550–561.

Solomon JA, Donnelly MJ, Walters LJ. 2014. Effects of sea-level rise on the intertidal oyster *Crassostrea virginica* by field experiments. Journal of Coastal Research 68:57–64.

Sumaila UR, Cisneros-Montemayor AM, Dyck A, Huang L, et al. 2012. Impact of the Deepwater Horizon well blowout on the economics of U.S. Gulf fisheries. Canadian Journal of Fisheries and Aquatic Sciences 69:499–510.

Swift F. 1897. Survey of the oyster regions of St. Vincent Sound, Apalachicola Bay, and St. George Sound, Florida. Washington, DC: U.S. Commission of Fish and Fisheries. Extracted from Report of Commissioner for 1896. Available from https://ecos.fws.gov/ServCat/DownloadFile/2669?Reference=2786.

Swift F. 1898. The oyster-grounds of the west Florida coast: their extent, condition, and peculiarities. In: Proceedings and papers of the National Fishery Congress, Tampa, Florida, January 19–24, 1898. Washington, DC: U.S. Commission of Fish and Fisheries. p. 185–187.

Twichell DC, Andrews BD, Edmiston HL, Stevenson, WR. 2007. Geophysical mapping of oyster habitats in a shallow estuary; Apalachicola Bay, Florida. Washington, DC: U.S. Geological Survey. Open-file report 2006-1381. Available from https://pubs.er.usgs.gov/publication/ofr20061381. Shapefiles: https://catalog.data.gov/dataset/benthic-habitats-and-surficial-geology-of-apalachicola-bay-florida-2006-geodatabase, accessed August 2019, accessed February 2018.

Twichell DC, Edmiston L, Andrews B, Stevenson W, et al. 2010. Geologic controls on the recent evolution of oyster reefs in Apalachicola Bay and St. George Sound, Florida. Estuarine, Coastal and Shelf Science 88:385–394.

Wang H, Huang W, Harwell MA, Edmiston L, et al. 2008. Modeling oyster growth rate by coupling oyster population and hydrodynamic models for Apalachicola Bay, Florida, USA. Ecological Modelling 211:77–88.

Whitfield WK, Beaumariage DS. 1977. Shellfish management in Apalachicola Bay: past, present and future. In: Proceedings of the Conference on the Apalachicola drainage system Vol. 26. St. Petersburg, FL: Marine Research Lab, Florida Department of Natural Resource. FMRP Publication #26. p. 130–140.

Wilber DH. 1992. Associations between freshwater inflows and oyster productivity in Apalachicola Bay, Florida. Estuarine, Coastal, and Shelf Science 35:179–190.

Zu Ermgassen PS, Spalding MD, Grizzle RE, Brumbaugh RD. 2013. Quantifying the loss of a marine ecosystem service: filtration by the eastern oyster in U.S. estuaries. Estuaries and Coasts 36:36–43.

General references and additional regional information

Apalachicola National Estuarine Research Reserve: https://apalachicolareserve.com/

Apalachicola River Wildlife and Environmental Area: https://myfwc.com/recreation/lead/apalachicola-river/

St. Vincent National Wildlife Refuge: https://www.fws.gov/refuge/st_vincent/

St. George Island State Park: https://www.floridastateparks.org/parks-and-trails/dr-julian-g-bruce-st-george-island-state-park

Apalachicola Bay Aquatic Preserve: https://floridadep.gov/rcp/aquatic-preserve/locations/apalachicola-bay-aquatic-preserve

Commercial oyster fishing regulations: https://myfwc.com/fishing/saltwater/commercial/oysters/

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