Chapter 3

Are Aquaculture Practices Sustaining Our Goal to Restore Oysters (*Crassostrea virginica*)?

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Additional information is available at the end of the chapter

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Abstract

Coastal areas are home to a wealth of economic and natural resources and are the most developed areas in the nation with fast increase in human population. Over 50% of the nation's population resides in 17% of the contiguous U.S. coastal areas. It is critical that consideration be given to the impact humans have on these coastal ecosystems and to the methods which are currently being utilized to enhance and restore these coastal habitats. In this chapter, we compare the status of the Eastern oyster, *Crassostrea virginica*, in two east coast estuaries: the Delaware Inland Bays, Delaware and Apalachicola Bay, Florida. Many ecological services, which are provided by oysters, such as their filtration, benthic and pelagic coupling, and habitat forming characteristics, have been extensively studied and discussed. Many regional economies in the United States of which the harvest of Eastern oysters was a major component, struggled with the collapsed fishery due to habitat limitation, water quality, sedimentation, parasitic diseases and other land use impacts. In response to these issues, oyster aquaculture has grown and is now a major part of the working waterfront where traditional wild oyster populations used to thrive. Research focusing on the ecological effects of oysters farm-raised with commercial aquaculture equipment is becoming more prolific as the industry moves away from a wild harvest fishery to a cultivated product. The oyster fishery may be recouped if the demand for oysters is supplied with oysters from aquaculture operations. Our primary goal in this chapter is to increase awareness about the potential benefits and some of the challenges facing the increased presence of aquaculture in these estuary systems.

Keywords: Eastern oyster, restoration, enhancement, population dynamics, oyster aquaculture, estuary health

1. Introduction

Coastal areas are home to a wealth of economic and natural resources and are the most developed areas in the nation with continuous increase in human population. Over 50% of the nation's population resides in 17% of the U.S. coastal areas. In light of these numbers, it is critical that consideration be given to the impact humans have on these coastal ecosystems and to the methods which are currently being utilized to enhance and restore these coastal habitats. There are various ways people use coastal areas for their needs. Shellfish aquaculture is one of the many activities people conduct.

In this chapter, we compare and contrast the health and status of the Eastern oyster, *Crassostrea virginica*, in two east coast estuaries: the Delaware Inland Bays, Delaware and Apalachicola Bay, Florida. Many ecological services which are provided by oysters, such as their filtration, benthic and pelagic coupling, and habitat forming characteristics, have been extensively studied and discussed. Oysters increase water clarity and quality by filtering sediments and algae, and removing nutrients such as nitrogen and phosphorous. The Eastern oyster was once a fixture of the local economies on the east coast however, combined effects from over harvesting, habitat destruction, and diseases such as Dermo and MSX have caused oyster populations to decline dramatically. Along with this decline in oyster populations, coastal lagoons in east coasts of the United States have been experiencing rapid development within the coastal watershed increasing eutrophication events. The once abundant oysters filtered algae and sediments, removed phosphorus and nitrogen, and played a vital role in the ecosystem that could help to counteract the increasing pressure on the watersheds. Many regional economies in the United States of which the harvest of Eastern oysters was a major component, struggled with the collapsed fishery.

In response to these issues, oyster aquaculture has grown and is now a major part of the working waterfront where traditional wild oyster populations used to thrive. In recent years, farm-raised oysters have become a more sustainable operation than commercial fishing. Oyster aquaculture has benefits beyond supporting human economies and diets. Oyster aquaculture can provide many of the same ecological services as oyster reefs, which are a valuable component of estuaries worldwide, serving as a unique habitat for many ecologically and economically important species. Research focusing on the ecological effects of oysters raised with commercial aquaculture equipment is becoming more prolific as the industry moves away from a wild harvest fishery to a cultivated product. However, there is a critical need to better understand the dynamics of local waters to enhance potential fisheries for both estuaries. The oyster fishery may be recouped if the demand for oysters is supplied with oysters from aquaculture operations. Our primary goal in this chapter is to increase awareness about the potential benefits and some of the challenges facing the increased presence of aquaculture in these estuary systems.

2. Temperate estuary "Delaware Inland Bays" characteristics and challenges

Delaware's 'Inland Bays' (DIB), similar to many of the coastal lagoons in the Mid-Atlantic region of the United States (U.S.), have been experiencing the impacts of chronic eutrophication and sediment erosion resulting from several decades of poor land use practices including housing development, agriculture and sustained nutrient input from within the surrounding watershed [1]. The cumulative impacts of these effluents from anthropogenic activities has degraded water quality and reduced the diversity and abundance of various species of aquatic life including fishes, invertebrates and submerged aquatic vegetation [2]. As a keystone species in estuarine bays, oysters provide important ecological services in these systems by filtering suspended particulates from the water column, increasing water clarity, and removing nutrients from eutrophic waters [3, 4]. Oyster reefs also serve as a valuable component of estuarine ecosystems, offering unique habitats for many ecologically, economically, and recreationally important species [2]. The bay degradation has led to the dramatic decline of the local oyster *Crassostrea virginica* populations since the late 1800s [4–7].

In response to the plummeting populations, 'oyster gardening' programs have taken root throughout the estuarine ecosystems of the Mid-Atlantic, including Delaware Inland Bays (*see* **Figure 1a**), in an effort to restore the native oysters for their ecological and commercial contribution to the health and viability of coastal estuaries. Many community-based estuary programs have involved volunteers to help rear larval oysters into healthy adults for reef restoration and it is no different in Delaware Inland Bays [5, 9, 10]. Volunteers living in the local communities surrounding the watershed in the Delaware Inland Bays place floating baskets of oysters at the ends of their docks to allow the filter-feeders a safe haven to grow from small, young spat into thriving adult oysters (*see* pictures in **Figure 1b**). Community members throughout southern Delaware are being given the unique opportunity to observe first hand many of the important ecological services provided by oysters and learn about the local watersheds.

With a shoreline of approximately 418 km, no part of Delaware more than 13 km from tidal waters, with Delaware Inland Bay consisting of three shallow coastal Bays: Rehoboth, Indian River, and Little Assawoman Bays. The combined surface water area of the three bays covers 83 square km with an average depth of 1.2 m. The Delaware Inland Bays (DIB) supports a small commercial hard clam and blue crab fishery along with weakfish, spot, bluefish, and Atlantic menhaden representing the majority of the commercial finfish catch in the Delaware Inland Bays and a variety of other commercially and environmentally important aquatic species [64].

Associated problems in those bays are similar to other Mid-Atlantic estuaries including eutrophication, high turbidity, sedimentation, periodic hypoxic/anoxic conditions, annual fish kills, low species diversity, and physical disturbances due to anthropogenic activities especially in the man-made canal systems. According to Delaware Inland Bays Estuary Program Report [11] and Chaillou et al. [1], approximately 80% of freshwater flow is from groundwater and the sandy, permeable soils of the watershed have led to widespread contamination of groundwater by nitrates in Delaware Inland Bays. Flushing rates may vary widely among the three bay areas, being as low as 1–7 days for Little Assawoman while those for Rehoboth and Indian River Bays may be as high as 80 and 100 days, respectively.

Delaware Center for the Inland Bays Report [12] stated agriculture as the largest use of land (32%) followed by developed/developing lands (22%), forested lands (17%) and wetlands and waters (16% and 12%) with significant loss of forest lands recorded in the watershed between

Figure 1. a. Delaware's Inland Bays showing oyster gardening locations, rip-rap planting locations, and known wild oyster locations [8]. *Map by Frank Marenghi.* b. Various oyster gears and oysters in rip-rap pictures indicating some natural recruitment is happening in Delaware Inland Bays. *Pictures by Frank Marenghi and Brian Reckenbeil.*

1992 and 2007 (*see* **Figure 2a**). **Figure 2b** shows the changes in the land use from 2007 to 2012, we can see improvement in the land use pattern for wetland lost. According to Delaware Inland Bays Estuary Program Report [11], the 200 hectares of dead-end canals within this system

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have been described as "unflushable." Martin et al. [15] reported that many of these canals are anoxic/hypoxic and subsequently lack higher trophic levels. **Table 1** describes the relative contribution of total nitrogen and phosphorus sources in the Inland Bays watershed and this outcome has not changed since the first time it was assessed in 1993 with nitrogen levels exceeding the targeted goal for all three bays in the Inland Bays. Agriculture is also listed as the leading contributor for the overall nitrogen and phosphorus sources in the Delaware Inland Bays [11].

Figure 3a shows the high nitrogen imputes, 6 times the healthy limit in Indian River due to fertilizer applications for agriculture and lawns in residential areas, animal waste and manure, and human wastewater [14, 16]. Eutrophication and degraded water quality impacts species present in this ecosystem [14]. **Figure 3a** displays the early nitrogen loadings in the Delaware Inland Bays from non-point source pollution [14]. This eventually causes regime shift from rich benthic flora and fauna to increase planktonic and microbial organisms [17]. **Figure 3b** shows the phosphorus loadings with no clear trends, according to Walch et al. [14], this may be credited to improved nutrient management on farms and the conversion of cropland to development with storm water controls.

Previous research suggested that [8, 18–24], Delaware's Inland Bays are in urgent need of the ecological services offered by oysters. Because these bays are very shallow (1 to 2.4 meter depth) and are poorly flushed by tidal movement, they are especially sensitive to environmental changes. Increases in pollutants, changes in salinity due to increase frequency of precipitation or drought events, climate change related fluctuation in water temperature, episodic hypoxic and anoxic conditions, as well as harmful algal blooms can all have detrimental effects on native oyster population. Proper site selection for oyster and reef restoration is essential and inclusive of other environmental limitation and issues. Over 50% of the available land in Delaware is used for agriculture with a long history of agricultural production of poultry, corn, soybeans, and other crops (*see* **Table 2**).

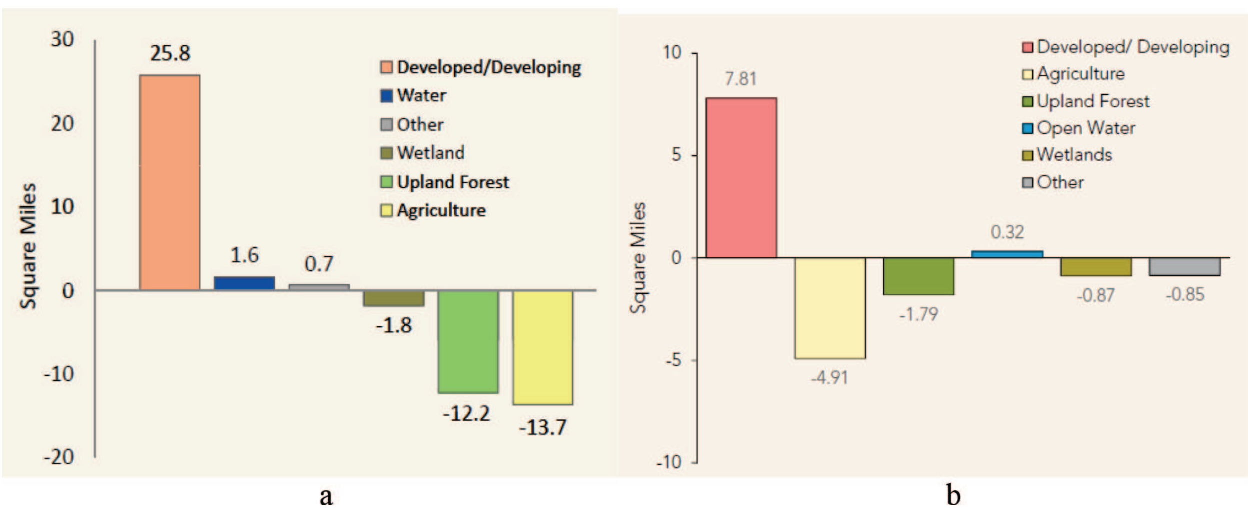
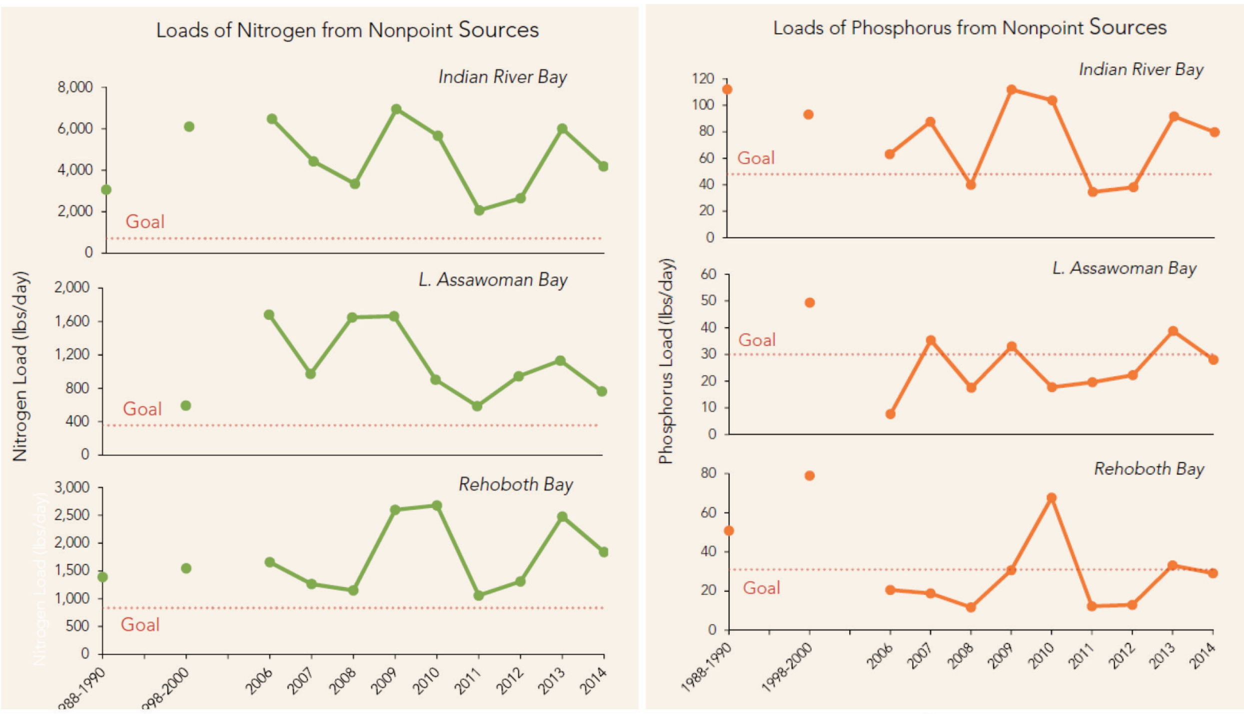


Figure 2. a. Changes in land use of the Inland Bays watershed from 1992 to 2007 [13]. b. Changes in land use of the Inland Bays watershed from 2007 to 2012 [14].

	Indian River Bay		Rehoboth Bay		Little Assawoman Bay	
Nutrient sources	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Agriculture	44.6%	39.4%	33.0%	17.0%	54.7%	52.6%
Boating	< 0.1%	< 0.1%	< 0.1%	< 0.1%	< 0.1%	< 0.1%
Forest	11.0%	19.2%	7.4%	9.4%	6.7%	19.5%
Point sources	12.5%	15.0%	27.3%	56.9%	0.0%	0.0%
Rainfall	6.2%	8.6%	8.8%	6.9%	12.8%	11.5%
Septic tanks	16.0%	9.3%	11.2%	3.8%	14.6%	5.6%
Urban	9.8%	8.6%	11.7%	5.9%	11.2%	10.8%

Table 1. Relative contributions of nitrogen and phosphorus sources in the Inland Bays (Courtesy of [11]).

These adverse environmental impacts have detrimental effects on overall habitat quality and put tremendous pressure on local aquatic habitats. As Delaware's coastal landscape continues to develop in a low-density and sprawling manner, the health of valuable natural resources, many of which sustain local economies, is increasingly at risk. Managing the demands for protecting critical habitat areas and managing water resources are complex and continuous challenges in Delaware [26].



a b

Figure 3. a. Yearly nitrogen loadings in the Delaware Inland Bays from non-point source pollution [14]. b. Yearly phosphorus loadings in the Delaware Inland Bays from non-point source pollution [14].

According to U.S. Environmental Protection Agency [16], two areas of concerns have been identified as critical issues for DIB: eutrophication and habitat loss primarily due to urbanization, agricultural activities, and low flushing rates. Specifically, primary sources of nutrients include, a point and non-point sources in watershed, septic systems, animal wastes and fertilizers from agricultural lands. Excess nutrients, nitrogen and phosphorus deteriorated the bay aquatic life were managed using Total Maximum Daily Loads (TMDLs) for nitrogen and phosphorus for the Indian River and its Bay and Rehoboth Bay in 1998 and the Little Assawoman Bay in 2004. According to Delaware Center for the Inland Bays Report [27] "to meet the load reductions required by the TMDLs, water quality goals include the elimination of all point sources if nutrient loading to the water bodies, along with a 40% reduction in

Farms, Acreages, and Inventories

	Farms[1]	Acres
Corn for grain	843	183,000
Corn for silage	73	7,000
Wheat	340	80,000
Barley	137	35,000
Soybeans	817	170,000
Vegetables	233	42,200
Total Fresh Market Vegetables	187	11,400
Cabbage	6	490
Cantaloupes	42	300
Cucumbers	47	170
Potatoes	19	1,600
Pumpkins	36	800
Snap Beans	45	970
Strawberries	101	100
Sweet Corn	49	3,300
Tomatoes	82	300
Watermelons	86	2,700
Other Vegetables	7	670
Total Vegetables for Processing	89	30,800
Green Lima Bean	33	13,000
Sweet Corn	35	6,700
Green Peas	27	3,900
Other Vegetables	20	7,200
		Inventory
Broilers	778	51,092,495[1]
Cattle & Calves	399	18,000
Hogs & Pigs	77	5,000
Sheep & Lambs	56	903[1]
Equine[2]	2,000	13,000
Goats	232	3,530[1]
Bee Colonies	48	546

[1]2007, Census of Agriculture
[2]2004, DE Equine Industry Survey

Table 2. Delaware farms, their acreages, and types of farming practices [25].

nonpoint phosphorus loading in the Indian River Bay, Rehoboth Bay and Little Assawoman Bay, 65% reduction in the upper Indian River Watershed, a 40% reduction of nonpoint nitrogen loading in the Indian River Bay, Rehoboth Bay and Little Assawoman Bay, and an 85% reduction in the upper Indian River Watershed."

Figure 4 provides promising results in regards to reductions in point source pollution with five-fold decrease in total nitrogen and phosphorus concentrations from 1990 to 2009 was recorded in Rehoboth and Inland River Bays. However, relative concentrations of nitrogen and phosphorus from agriculture increased up to 57% from its previous levels of 45% and 39% for nitrogen and phosphorus, respectively [13].

Anthropogenic activities not only degrade water quality but they also contribute to the reduction in biodiversity and abundance of coastal bay species [2]. Eutrophication, high turbidity, sedimentation, periodic hypoxic/anoxic conditions, annual fish kills, low species diversity, and physical disturbances due to anthropogenic activities all contribute to reduction in biodiversity and abundance [2, 27, 28]. **Figure 5** provides a description of land use in the Delaware Inland Bays Watershed from 1992 to 2007. Significant increases are apparent in developed areas and areas marked for development. In opposition, declines were observed in areas that were upland forests or small agricultural areas [13].

To enhance habitat quality, for the past 15 years oyster gardening program initiated and public engagement has been the major part of the program effort to have the coastal citizens to be stewards of those bays and contribute to restoration efforts in the Delaware Inland Bays. Those oysters are further stored in the bays as adults with the hope that they will thrive in the natural setting. The resulting larger, healthier oysters are used for restoration work in the area such as artificial reef creation and rip-rap planting, and contribute spat to enhance wild populations. Although there is a general consensus among scholars that the current rates of resource depletions and environmental degradation cannot be sustained over a long period of time, these floating gardens are important in their abilities to offer essential habitat

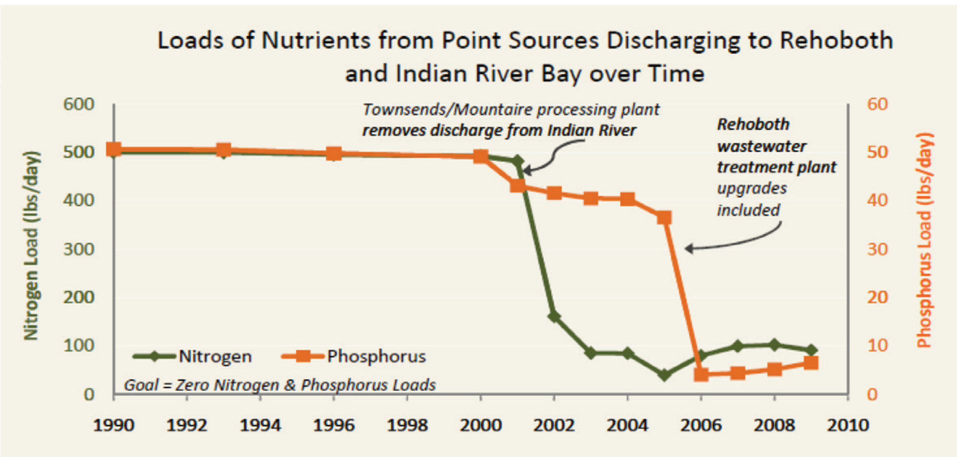


Figure 4. Nutrient loads reduction of point sources discharges in Rehoboth and Indian River Bay from 1990 to 2009 ([13]; www.inlandbays.org).

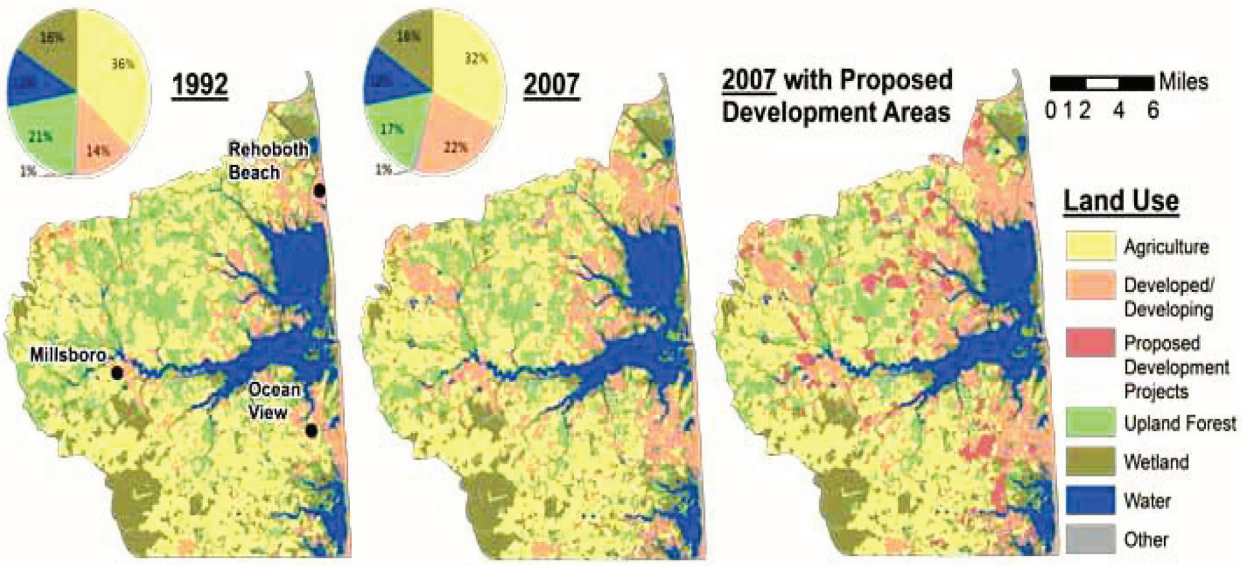


Figure 5. Changes in land use in the Inland Bays watershed [13].

revitalization. According to Kellogg et al. [29], oyster reefs reduce eutrophication by enhancing denitrification rates and assimilating nutrients into macrofauna.

Shellfish aquaculture has become a new hope for the coastal community in Delaware, with the approval of new regulations allowing commercial shellfish aquaculture practices. The past 10 years leading up to these regulations, Delaware Inland Bays have been home to a small community-based oyster mitigation program, which biennially distributes oyster spat on shell to volunteer citizen growers. The use of cost-effective culture techniques to culture oysters for restoration has developed into an integral part of the ecological restoration efforts.

Oyster gardening program was established to educate the public on the long-term stewardship and enhancement of the Inland Bays watershed as a collaborative effort with the leadership of the Center for the Inland Bays. The community oyster gardeners throughout the Inland Bays watershed support the program by caring for oysters held in floating cages 'Taylor floats' tied to their docks. Taylor floats are rectangular vinyl-coated 16 gauge, 25 mm wire mesh cages with a ring of PVC piping attached to the top to serve as the floatation gear (*see* **Figure 1b**). Each floating cage contains two square wire mesh baskets (46 x 46 x 23 cm) in which the oysters are placed [24].

Spat on shell were provided during the initial 3 years of oyster gardening program and later a remote setting process was implemented to supply the oyster gardening volunteers spats on shells. Remote-setting of oyster (*Crassostrea virginica*) larvae from the Northeast-Haskins resistant strain (NEH) line is performed biennially in Delaware to supply small-scale oyster enhancement efforts. Oyster larvae are raised in the flow through tank from the pediveliger stage through metamorphosis and settled on cleaned disarticulated oyster shells (cultch). Shell bags containing 5–10 mm spat have been distributed to oyster gardeners throughout the Inland Bays. In the floating cages, gardeners are able to keep the spat clean and protected, greatly minimizing the negative impacts of predators. Since 2009, simple alterations in choices of shell containment gear were made to try to increase settling efficiency rate and spat set. Shell containment gears included common diamond plastic mesh bags, wire baskets, and plastic aquaculture trays. Setting efficiency was estimated and for small-scale growers, the stacked aquaculture trays had the highest set efficiency and proved advantageous for several reasons, including: reduced handling time, uniform shell distribution within tanks, and easy-to-clean detritus between shell layers [84]. With improved growth and survivorship due to increased water flow, greater access to particulate foods, and much reduced risk of burial by sediments [9, 10], the resulting larger, healthier oysters have the potential to contribute spat for the enhancement of wild populations and are 'planted' in areas of the bays for local restoration work. Determining the remote set process success is often neglected, yet gathering this critical information will inform managers of the approximate number of spat distributed in small-scale programs and commercial scale aquaculture operation alike.

The creation of artificial reefs in designated areas is often used for oyster restoration, but the Delaware program started using riprap planting. Riprap is an irregular, large loose stones used to hinder the eroding effects of wave action. When oysters are planted in riprap, they are nestled in stable crevices between the rocks, mimicking the relatively secure, three-dimensional structure of naturally occurring oyster reefs that are integral to the oysters' survival [24]. Considering how limited oyster population in the Delaware Inland Bays, any effort to restore this keystone species in rip-rap crevices far closer than not making any effort and aquaculture is a step closer to a solution.

Although oyster aquaculture may be impacted by excess nutrients, it can also be a solution to mitigate this problem. According to Rose et al. [30], nitrogen removal by farmed shellfish was a more favorable solution per acre than BMPs for agricultural and storm-water run-off. Although new regulation allows oyster aquaculture in strategically identified areas in Delaware Inland Bays, Delaware is currently the only state on the Northeast Atlantic seaboard without commercial shellfish aquaculture. Legislation is developing policy and protocols for implementation, as the push for legalized aquaculture grows. Neighboring states have shown the economic and cultural benefits of functioning industry. Three Inland Bays in Southern Delaware, due to protection from open waters and ease of access for workers, offer promising future locations for bottom leases. Oysters are functionally extinct within the Bays and with the rapid development of the local watershed, the ecological services oysters contribute are more important than ever. Oyster aquaculture can help restore depleted wild populations of oysters while filtering the water, providing structural habitat, and creating a new sources of jobs. There is a unique opportunity to study directly how aquaculture facilitates restoration considering the impacts and benefits community driven oyster gardening program has provided since 2003. Delaware Department of Natural Resources and Environmental Control (DNREC), Delaware Division of Fish and Wildlife provides proposed shellfish regulations, proposed shellfish aquaculture development areas, legal notices and updates on regulations related information in their website at http://www.dnrec.delaware.gov/fw/fisheries/pages/shellfishaquaculture.aspx.

Figure 6 shows the shellfish growing areas in Delaware Inland Bays while **Figure 7** shows proposed shellfish aquaculture development areas in the Inland Bays.

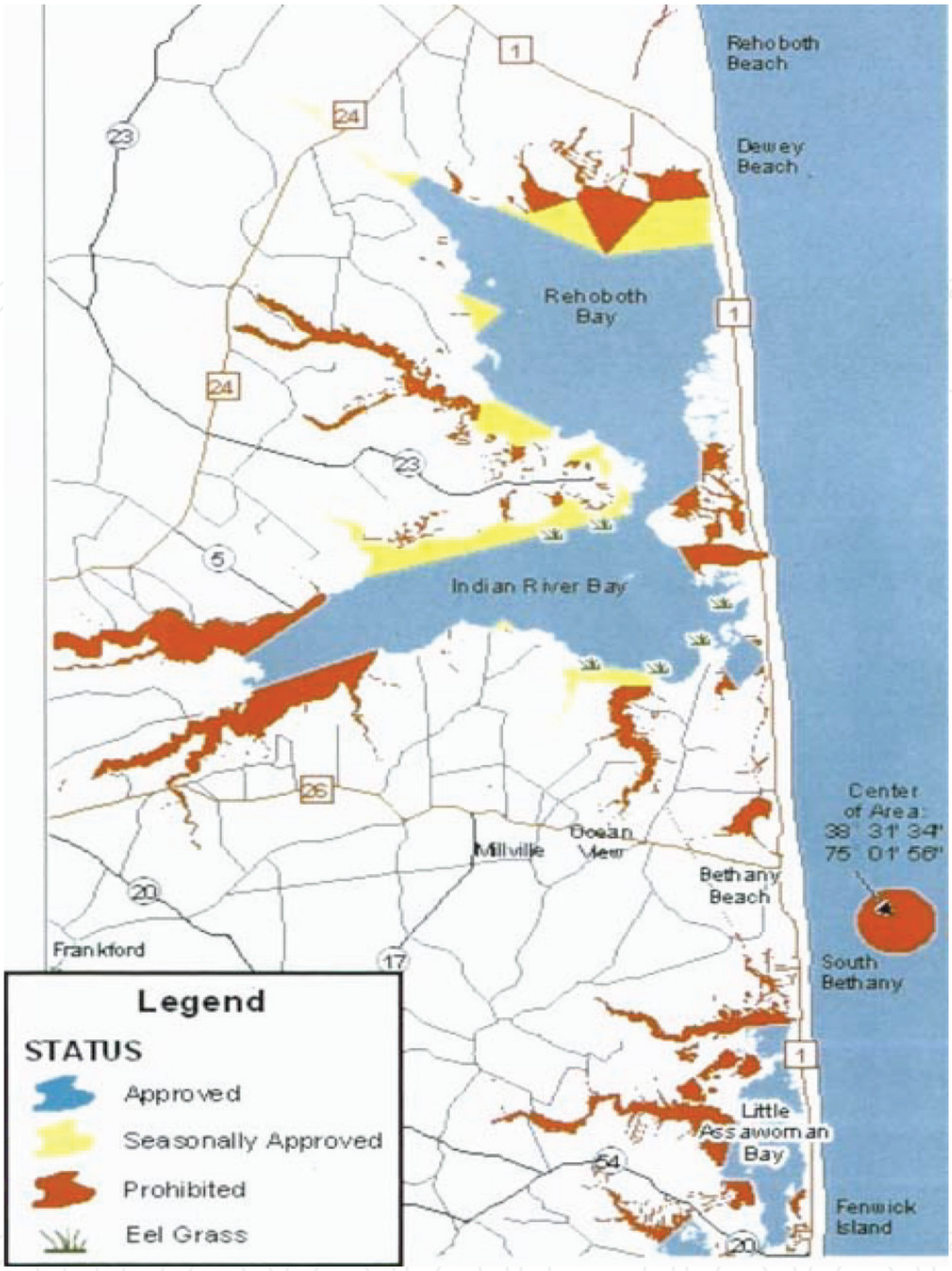


Figure 6. Delaware Inland Bays. Shellfish growing waters ([31]; http://www.dnrec.delaware.gov/swc/wa/Pages/Shellfish-Growing-Waters.aspx).

3. Subtropical estuary "Apalachicola Bay" characteristics and challenges

Apalachicola Bay is a subtropical, barrier island estuary located along the northeast Gulf of Mexico in northwest Florida. The bay, a National Estuarine Research Reserve (ANERR), is a river-dominated system [33, 34] with a highly variable salinity regime. Its main source of freshwater, the Apalachicola River, the largest river in Florida with the highest riverine discharge rate [35, 36] is formed at the confluence of the Chattahoochee and Flint rivers, both with

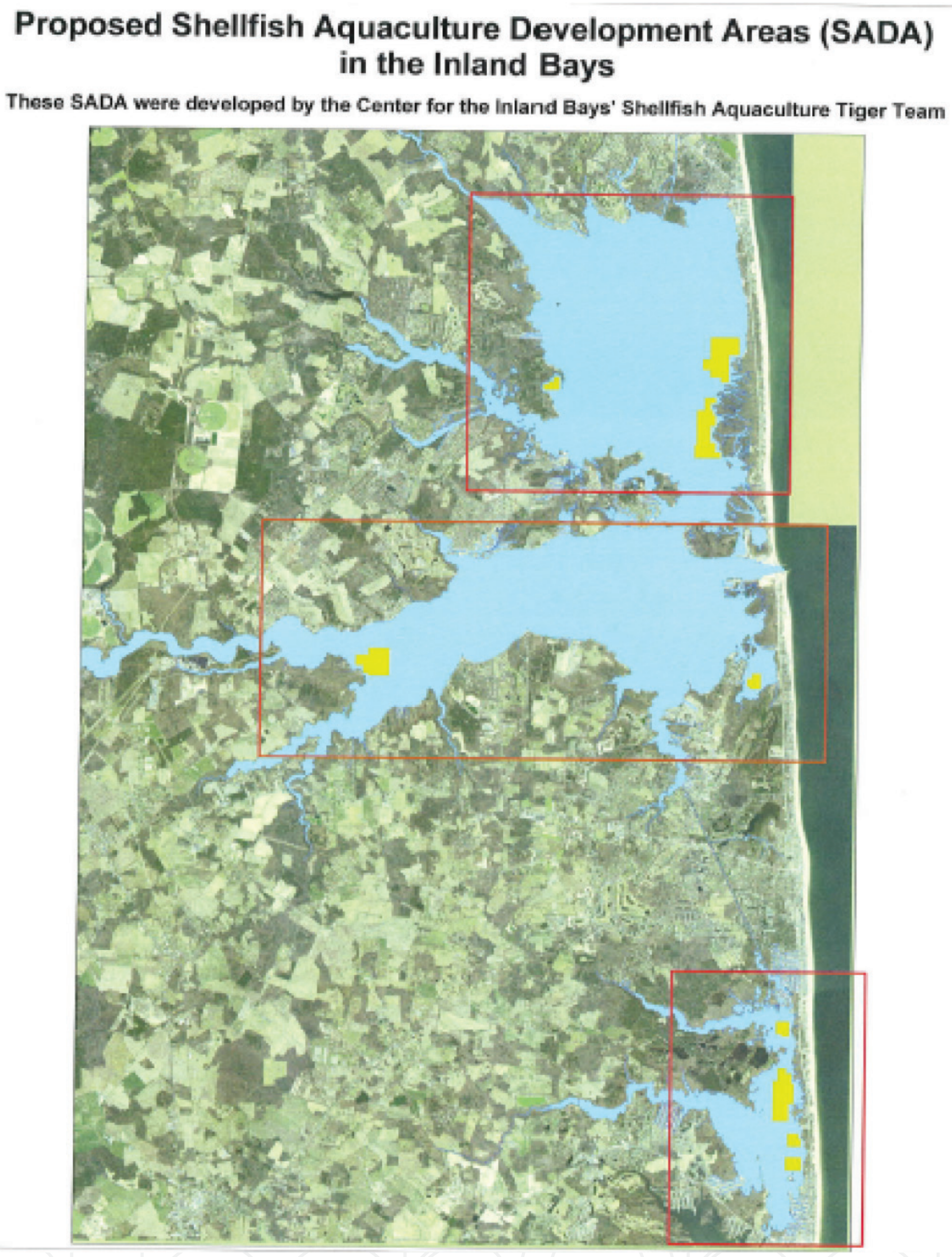


Figure 7. Proposed shellfish aquaculture development areas in the Inland Bays. ([32]; http://www.dnrec.delaware.gov/fw/fisheries/pages/shellfishaquaculture.aspx).

headwaters in Georgia. The Apalachicola-Chattahoochee-Flint (ACF) tri-river system drains 19,600 mi^2 of uplands and floodplains in Alabama, Georgia and Florida. The bay's hydrology consists of winter/spring flooding and summer/fall drought. The spring floods are essential to the health of the bay, which relies on Apalachicola River for freshwater and for the abundant nutrients – nitrogen, phosphorus and organic carbon – the delivers to the productive bay.

Species diversity is high in Apalachicola Bay, which has one of the most diverse ecosystems in the southeastern United States. Seafood production is a major industry in Franklin County, where the bay is located and where shellfish harvesting, especially of the Eastern oyster, *Crassostrea virginica,* contributed significantly to the local economy. The bay's oyster bars produced 90% of the oysters harvested in the state of Florida, and 10% of the nation's oysters and are known for their high quality and excellent taste. The industry generated $10–$14 million in revenue annually, and in Franklin County, oysters made up nearly one-third the value of commercial marine landings. **Figure 8** shows the interpreted surficial geology with the locations of oysters in Apalachicola Bay, Florida.

The river/bay ecosystems are in highly pristine areas and have not been adversely impacted by coastal development. The major stressor on the system, both the tidal and non-tidal reaches of the river, has been low river stage due mainly to three factors: dam installation, channel widening, and drought and natural fluctuations [36]. Over the recent past freshwater inflow to Apalachicola Bay has been critically diminished by the cumulative impacts of the aforementioned stressors, weather-related events and a decades-long water rights battle between Florida, Alabama, and Georgia (i.e. 'Tri-State River War'). Normal late-autumn drought conditions for the ACF watershed were exacerbated by two La Niña climate events in 2002 and 2007, during which time the southeast United States experienced warmer and drier than normal conditions. Drought-stricken Georgia increased its usage of the Apalachicola River's headwaters to support water demands from Atlanta's growing population and for crop irrigation. This resulted in a 17% reduction in water flow to the Apalachicola Bay. Other years experiencing unusually low river flow into the bay include 2000, 2008, 2011 and 2012 (the lowest on record); data show that the six lowest river flow years occurred between the years 2000–2012 [38]. The salinity in Apalachicola

Figure 8. Apalachicola Bay. Surficial geology shows the interpreted surficial geology with the locations of oyster bars superimposed on the sun-illuminated bathymetry ([37], U.S. Geological Survey Open File Report 2006-1381; https://cmgds.marine.usgs.gov/publications/of2006-1381/html/maps.htm).

Bay was exceptionally high in 2012 [39]. In January 2018, the Supreme Court of the United States heard arguments concerning the Alabama-Georgia-Florida water war. A ruling has not been issued at this time. Florida is seeking a water-sharing pact such that Georgia's usage of the ACF headwaters does not create adverse downstream effects for Apalachicola Bay fisheries.

In addition to decreased freshwater inflow, climate change models predict a north Florida sea level rise of up to 15 inches by the end of the century. Scientists speculate that this vertical rise may push the shoreline 70–250 feet inland in low-lying coastal areas (*see* **Figure 8**). According to a one report, this would submerge 61% of salt marshes and three quarters of the tidal fresh water marshes [40].

In August 2013, NOAA declared the Apalachicola Bay oyster fishery a disaster, caused by a long and excessive drought during the 2012–2013 season. Due to those events, Florida west coast oyster landings dropped 60% and revenue declined 44% [85]. The Deepwater Horizon Oil Spill did not impact Apalachicola Bay oysters significantly. Oysters tested by the University of Florida [39] were below instrumental detection for oil spill contaminants, polycyclic aromatic hydrocarbons (PAHs). According to research in the same report, a high percentage of bay oyster shells are parasitized by boring clams, sponges, polychaete worms or other organisms. In addition to a decrease in shellfish growth and productivity, shell deformity also detracts from shell integrity and may therefore affect the economic value of product. Dermo disease is present in Apalachicola Bay oysters, but apparently, its severity is less than in other bays along the East Coast, such as the Chesapeake Bay [41]. The UFL researchers report that more than 90% of tested oysters are positive for the parasite.

In an attempt to save a struggling industry, Florida's leaders have approved oyster and clam aquaculture leases in Wakulla County and in Franklin County (*see picture in* **Figure 9**). In April 2018, Florida's governor and his cabinet are looking to approve expanding current

Figure 9. Apalachicola Bay relies on freshwater input from the Apalachicola River to maintain ecosystem health and to support a productive shellfish fishery. *Map from State of Florida, updated by Stacy Smith.*

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Figure 10. A state worker showing FAMU students oysters in tongs in Apalachicola Bay. *Picture by Stacy Smith.*

aquaculture lease in Alligator Harbor, (21 new leases) Franklin, County, and Ochlockonee Bay (72 new leases), between Wakulla and Franklin counties. Each lease is 1.5 acres (The Apalachicola and Carrabelle Times 2018). Picture shows oysters in tongs in Apalachicola Bay and sediment (*see* **Figure 10**).

4. Where shared challenges meet shared solutions?

As stated by Rossi-Snook et al. [24] "an integral aspect of oyster gardening programs that cannot go unmentioned is the development of a sense of environmental stewardship among community members. In these programs, professional scientists and volunteers are working together to conserve both an ecosystem and a culture; by reintegrating oysters back into the bays, natural recruitment and proliferation is possible, eventually allowing for the safe and ecologically-sound harvest of oysters and other ecologically important macrofauna to redevelop within the community."

Ecosystem engineers, as described in many environmental books and articles, are organisms that can dramatically change the environment and essentially create ecosystems. Jones et al. [42] discussed differences between allogenic and autogenic ecosystem engineers. He stated oysters fall in to both categories: allogenic because they "change the environment by transforming living or non-living materials from one physical state to another, via mechanical or other means," and autogenic because they "change the environment via their own physical structures (i.e. living and dead tissue) as they grow and become larger, their tissues create habitat for other organisms to live in."

Although, *Crassostrea virginica* can tolerate a wide range of salinity, temperature, turbidity, and oxygen levels, Kennedy [6] discussed how water depth and salinity affect oyster populations and their associated fauna. Oysters generally occur in areas with the annual temperature range between −2 to 36°C except for the oysters in Gulf of Mexico which can survive intertidal temperatures between 44 and 49.5°C for over 3 hours. Larger established populations are found at salinities ranging from 5 to 40 ppt. Nevertheless, adult oysters have the ability to survive even in fresh water for short time durations [6]. When oysters are located in areas of an estuary with less salinity, they have slower growth rates. This is primarily due to a lack of food availability. In addition, because "drills, starfish, and boring sponges cannot stand the reduced salinities that prevail" in areas farther up in estuaries, oysters are able to have a higher rate of survivorship in these zones ([43], cited by [44]).

The Eastern oyster (*Crassostrea virginica)* serves as an essential connection between pelagic and benthic food webs. Oysters consistently remove suspended organic and inorganic particles >3 μm in diameter with much effectiveness [45]. Since it only takes up around 70% of the filtered organic material, this leaves dense, mucus-bound biodeposits, also known as pseudofeces which are ejected. These biodeposits can serve as a valuable food source for benthic organisms. Oyster reefs also prompt phytoplankton productivity in natural, non-eutrophic systems by vigorously filtering suspended materials, lowering turbidity that may restrict light penetration and oyster growth [45]. Increased water clearness will in turn promote growth of benthic algae and diatoms that are a substantial food source for sessile and mobile benthic herbivores that in turn are eaten by many carnivorous fish [3]. However, the function of oysters mineralizing organic carbon and converting nitrogen and phosphorus into forms usable by primary producers may be more critical than serve as the primary consumer in the salt marsh [46]. Oysters can enhance the reduction of ammonium to nitrites and nitrates through their biodeposition by taking N from the water column and depositing it into sediments. Microbes can then reduce the nitrogen to N_2 gas, which sublimates into the atmosphere. This is especially relevant in anthropogenically enriched environments [3, 46].

As [58] discussed oyster reefs have been considered as an essential fish habitat (EFH) for the last few decades. Many fish rely on oyster reefs for feeding, reproduction, and protection from predation. Within the same brief period during mid-summer, peak recruitment for all oyster reef residents occurs. This associates managing harvest and restoration efforts. Disruption of oysters by the addition of shell or dredging the reef during the spring through early autumn breeding season could negatively affect reproduction of many fish by burying nests, breaking apart articulated shells or scaring off males guarding their eggs [47].

Many economically important species may utilize oyster reefs for valuable juvenile nursery habitat Posey et al. [48]. Nursery habitat function of reefs may be expanded by locating restored reefs in shallow (<2 m deep) waters where large fish predators are less abundant. Important refuge habitats in estuaries are shallow water reefs. These reefs can also provide alternative foraging habitats for fish and crabs that are may be displaced by anoxic or hypoxic conditions as in the Chesapeake Bay, the Delaware Coastal Bays, the Gulf of Mexico and elsewhere [49].

Other nearby habitats can be influenced by oysters as well, like those of a salt marsh. This influence is achieved by protecting the salt marsh from the influences of wave energy. Shoreline retreat was significantly lower in a Louisiana study at sites with a constructed intertidal reef only 0.7 m tall in low energy areas. Low and high energy sites both showed positive oyster growth and recruitment (4.9 spat per shell) and showed potential to help stabilize sediment, reducing erosion, as well as providing salt marsh habitat in addition to a habitat of its own [50]. Because oyster reefs in salt marshes trap sediments as they grow, they can eventually become colonized by *Spartina* spp. and other grasses. Subsurface or fossil oyster reefs have been discovered extending from an existing reef into the marsh [46].

Indeed, bivalves can affect a shift in the phytoplankton community. Many authors have suggested that bivalves exert a "top-down" control of phytoplankton dynamics [51–54]. Some have stated in certain instances there exists a synergistic feedback. Oysters considerably advance the timing of nutrient recycling rates, allowing indulgence consumption and fast growth of some algal species [55, 56]. Through continuous filtering activities of the oysters, the phytoplankton community is shifted from older lag phase cells to younger cells in a logarithmic growth phase. Reduced competition causes the phytoplankton community to shift to faster growing algal species that are able to take advantage of the increased light and nutrients [57].

Crassostrea virginica are bivalve suspension-feeder organisms that are native to the Delaware Inland Bays and Apalachicola Bay areas. Bivalve suspension feeders have been shown to serve an important biogeochemical role in coastal ecosystems because N and P from the water column are transferred to the sediments in their biodeposits [3]. This means that the filtration of the oysters can be shown to remove nitrogen from an aquatic ecosystem. Although the benefits of physical oyster structure may be significant, the benefits from oysters' ecological function are under-appreciated [58]. Although many studies have been done to focus on various effects of oyster ecology on lower trophic levels, resident species, and water quality, very few studies have yet conclusively demonstrated net benefits to higher trophic levels.

One of few studies showed where oysters enrich the surrounding benthos with their biodeposits and dissolved nutrients increases meio- and macrofauna species assemblage in their study [46]. Also observed by Bahr and Lanier [46], many oyster reef residents feed upon these lower trophic levels and find aid in the unique niches created by the oysters. Polychaete were collected from the sediments under the oyster gears, 1 meter away from the gears and 5 meters away from the gear in the Delaware Inland Bays. Polychaete survey results during the warmer months indicate the highest abundance of polychaetes were found at the Little Assawoman site and the lowest abundance of polychaetes in Rehoboth Bay. The results of the benthic community assessment indicate that there was no significant impact to Polychaete abundance or species richness from the oysters and aquaculture gear. Little Assawoman Bay had higher abundance and species richness than other two bays [59]. Benthic community assessments are often used to evaluate the health of an ecosystem. A healthy benthic community in the mid-Atlantic is characterized by high biodiversity of benthic flora and macrofauna [17]. Benthic communities are made up of a several different types of organisms including many invertebrate species [86]. Benthic organisms play important roles in ecosystems because they are a fundamental part of the food web. They act both as a food source for larger organisms and as decomposers, helping bacteria break down organic matter [86].

Improved water quality and continuity of a healthy food chain, benthic/pelagic coupling, and planktonic stability by oysters have provided valuable benefits to estuaries [60]. Posey et al. [48] examined whether resident and transient species are in fact attracted to the physical structures of the oysters for feeding or if they receive the majority of their foods elsewhere and actually utilize these habitats created by oysters for other needs.

In addition to their impacts as a filter feeder to clarify water, harvested oysters left unharvested would remove excess nutrients from the bay incorporated within the oysters shell and tissue [3]. Floating aquaculture gear would increase species diversity in the Delaware Inland Bays by providing refuge and foraging areas for transient species moving throughout the Delaware Inland Bays [21, 24, 61]. The years of research efforts conducted by the primary author and her research team found [62, 63], unlike some finfish farming, rearing shellfish in high densities in shallow water can have positive effects on the environment and may promote biodiversity. In the Delaware studies conducted around the submerged aquaculture equipment, 17 species showing significantly greater abundance and richness than in adjacent low-profile oyster shell reefs in 2006. Fourteen species around the equipment vs. the eutrophied, turbid, soft-bottom lagoon (including 3 species that require oyster shells for spawning substrate) in 2007. About 49 species of fish and invertebrates along with 8 species of macroalgae greatly contributing to the diversity of the native ecological community in 2008. In Virginia, 45 species of macrofauna were recorded inhabiting one commercial oyster farm that used floating equipment. In a study in Rhode Island, species richness was significantly greater in submerged aquaculture equipment than in a nearby seagrass bed or an unvegetated sand flat, especially for fishes and invertebrates in their early life stages, demonstrating the equipment may benefit some species more than others. These studies are critical to understanding the complex ecological interactions that occur and will allow farmers, managers, and regulators to fully appreciate the consequences of their actions. **Figure 11** shows the aquaculture gears used for the oyster gardening program and previous studies.

The potential effect of utilizing shellfish aquaculture for community-based restoration and environmental conservation is promising. **Figure 12** shows 2011 shellfish harvesting status of the Delaware Inland Bays [64]. Suitable locations for spat recruitment and oyster growth can be used to advance natural oyster settings. Number of oyster gardeners currently involved in the Delaware Inland Bays (DIB) oyster restoration efforts is about 200 community volunteers using their docks. Working with this number, and that fact that each oyster filters approximately 190 liters of water per day, the oysters currently involved in the program filter about 7,570,825 liters of water per day in the Delaware Inland Bays. Although this may seem to be an impressive amount, it is not when observing the actual volume of the Delaware Inland Bays. The Delaware Inland Bays have a surface area of 83 square kilometers, with an average depth of 1.2 meters [15]. This is a total volume of 101 billion liters. In order to filter the volume of water in the Delaware Inland Bays once daily, at least 534 million more oysters need to be cultivated and allowed to live without harvest. There are currently about 40,000 oysters. Once the critical amount of at least 534 million oysters is established, only then will there be at a point where there will be excess for actual harvesting. Only just beginning to touch the tip of the proverbial iceberg in Delaware with the restoration project, many more efforts are required.

Habitat restoration and major pollution reductions are needed to restore water quality and achieve a healthy estuary once again. Unfortunately, areas close to the shoreline and most tributaries have unhealthy oxygen levels with severe condition in some areas although most open water areas have good dissolved oxygen for healthy aquatic lives. One of the major causes for poor water quality condition for low dissolved oxygen is due by the excess nutrient leading major habitat loss and degradation issues for variety of finfish, shellfish and other aquatic species including invertebrates [64].

Figure 11. Aquaculture gears used during the oyster gardening program. *Pictures by Frank Marenghi and Patrick Erbland.*

According to Delaware Center for the Inland Bays Report [64], the Delaware Inland Bays are a premier east coast fishing destination, but important state fishes like the weakfish and blue crab population are declining. While the Inland Bays Oyster Gardening Program and student research projects confirm oysters can grow successfully in all three bays, wild oysters are very limited.

Fulford et al. [65] shares findings suggest that the ecological benefit of restoring bivalve populations are somewhat variable. A comparative model analysis of restoration plans in specific systems can be highly beneficial to maximizing the benefit-to-cost ratio of restoration efforts intended to reduce the negative effects of cultural eutrophication. It should also be noted that we should be cautious of generalizations about the effect of suspension-feeding benthos on phytoplankton without due consideration of estuarine size, circulation patterns, and morphology, as well as any other factors that may regulate community filtering

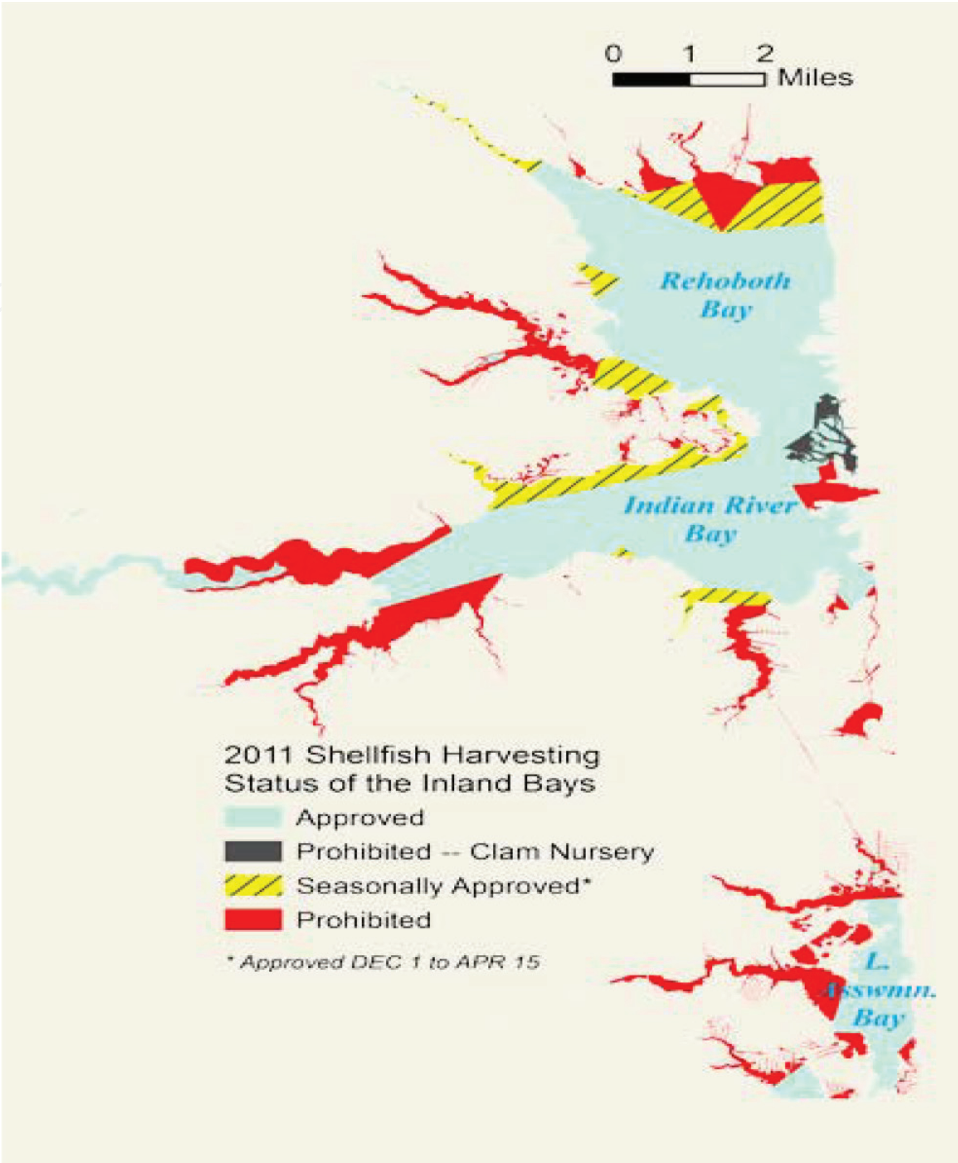

Figure 12. 2011 shellfish harvesting status of the Delaware Inland Bays (Delaware Center for the Inland Bays 2013).

rates [66]. Keeping these thoughts in mind for future research potential, let us conclude with a short synopsis of how well oyster gardening is working in the DIB, and what steps need to be taken nest to maximize enhancement and restorations of both temperate and subtropical estuaries.

For the past 15 years, oyster gardening has been part of the restoration of the Delaware Inland Bays. Volunteers living in the local communities surrounding the DIB place floating baskets of oysters at the ends of their docks, allowing them protection from predation in order to grow from small, young spat into thriving adult oysters. Oyster aquaculture has a potential to generate income for coastal communities [67]. The volunteers who participate in the monitoring of water quality and oyster aquaculture have learned many things while becoming trained in aquaculture. They have realized an increase awareness to protect our water and its biota. They have also gained an appreciation for the Eastern oyster species, C*rassostrea virginica*, and the efforts of its restoration. Oyster culture has a potential to lessen pressure on natural overexploited populations and to generate income for coastal communities [67]. There are various social and economic benefits of oyster gardening in their local habitats in relation to watershed improvements discussed by Ozbay and Cannon [68]. The implications of these gardeners' actions are exponential in their ability to offer essential habitat revitalization.

Environmental factors determine the productivity of the Apalachicola Bay oyster community: factors which encourage oyster growth include bottom substrate, nutrients from Apalachicola River and food availability. Those which are detrimental to oyster productivity include predation, disease, and sedimentation [69, 70]. Approximately, 10% of the bay's aquatic area is covered by oyster bars. Apalachicola Bay supplies the Florida seafood industry with 90% of its oysters. Local oyster harvesters and seafood suppliers rely on oysters for their livelihoods. The oyster industry brings $10–$14 million in revenue annually to Franklin County, FL; therefore, oyster productivity is linked to both ecosystem health and to financial solvency of the local economy.

Approximately 17% of the bay's total area is occupied by fresh, brackish and salt water tidal marshes and only 7% of its area is occupied by seagrass, with the majority of these seagrass beds confined to high salinity and low turbidity regions of the bay [71]. The riverine discharge and associated seasonal flood-related flux of inorganic and organic nutrients into the bay from the Apalachicola River and its associated marsh systems is essential to the present ecosystem dynamics of the estuary [33, 72]. The bay also supports highly productive shellfish and finfish fisheries all of which are either directly or indirectly dependent upon the hydrologic conditions of the bay. For example, when the salinity of this estuary increases, oyster mortality rates increase due to predation by Gulf of Mexico gastropod mollusks and other predators, which require higher salinities [71, 73, 74]. Input of freshwater in river-dominated systems reduces predation pressure from marine species during high flow periods.

A study by Chanton and Lewis [72] compared ecosystem biogeochemical dynamics in Apalachicola Bay during periods of low river flow (summer-autumn) versus high flow (winter–spring). They demonstrated that floodplain detritus does not drive estuarine production in Apalachicola Bay but rather the highest estuarine productivity in Apalachicola Bay coincides with low flow period during the summer [72, 75–77]. The bay's primary productivity during these low flow periods, however, is driven by autochthonously produced dissolved nutrients coming from upstream [72] and/or possibly from marsh outwelling. Chanton and Lewis [72] also found that although consumers primarily utilize autochthonously produced substrates during periods of high river flow, the influx of terrestrial floodplain detritus does augment productivity in the bay. They concluded that reduced river flow would have a detrimental effect on overall estuarine production, especially during seasonal and extended droughts. The trophic status of the bay is therefore intricately linked to Apalachicola River's hydrologic regime, which impacts the bay.

As stated earlier, Deepwater Horizon Oil Spill has not significantly impacted Apalachicola Bay oysters. Compared to other areas along the Gulf Coast, the water quality in Apalachicola

Bay has remained relatively unaffected, with the exception of tar balls washing ashore and some oil sheens. To enhance oyster landings after the spill, the state of Florida opened a 7-day-per-week oyster harvest at both the summer and winter harvesting grounds during June–August 2010; however, preliminary commercial landings reports suggest that Franklin County's 2010 oyster harvest was the lowest in 5 years, although landings from 2007 and 2009 were the highest in 20 years. Furthermore, the annual 2010 landings rate (pounds/trip) was the lowest since 1991 (**Figure 13**). This drop in oyster production and the over-tapping of the winter oyster beds translated into lost revenue, which reverberated throughout the Florida seafood and restaurant. The oyster fishery has not rebounded since 2011 and prices have increased (**Figure 13**). University of Florida researchers developed a population model to determine whether harvest of sub-legal oysters contributed to the crash in the Apalachicola Bay fishery while they found an increase in natural mortality [39, 78].

Since natural oyster populations have been unable to keep up with demand let alone sustainable historic stocks, aquaculture has become an essential part of restoration and stock enhancement efforts. According to the California Aquaculture Association [79], the top U.S. marine aquaculture species was oysters. In 2015, U.S. shellfish farmers produced 15,876 metric tons of oysters at $173 million market value [80]. According to Stewart [81], the farmed oyster production grew by 806% between 2006 and 2012 in Chesapeake Bay. Rheault (Executive Director of East Coast Shellfish Association) in Stewart's report stated that the east coast shellfish production for oysters has doubled in 5 years at a steady rate of 12% per year. With $2 a pop on U.S. restaurant menus, associated demand for oysters are making oyster farming vital player in the United States.

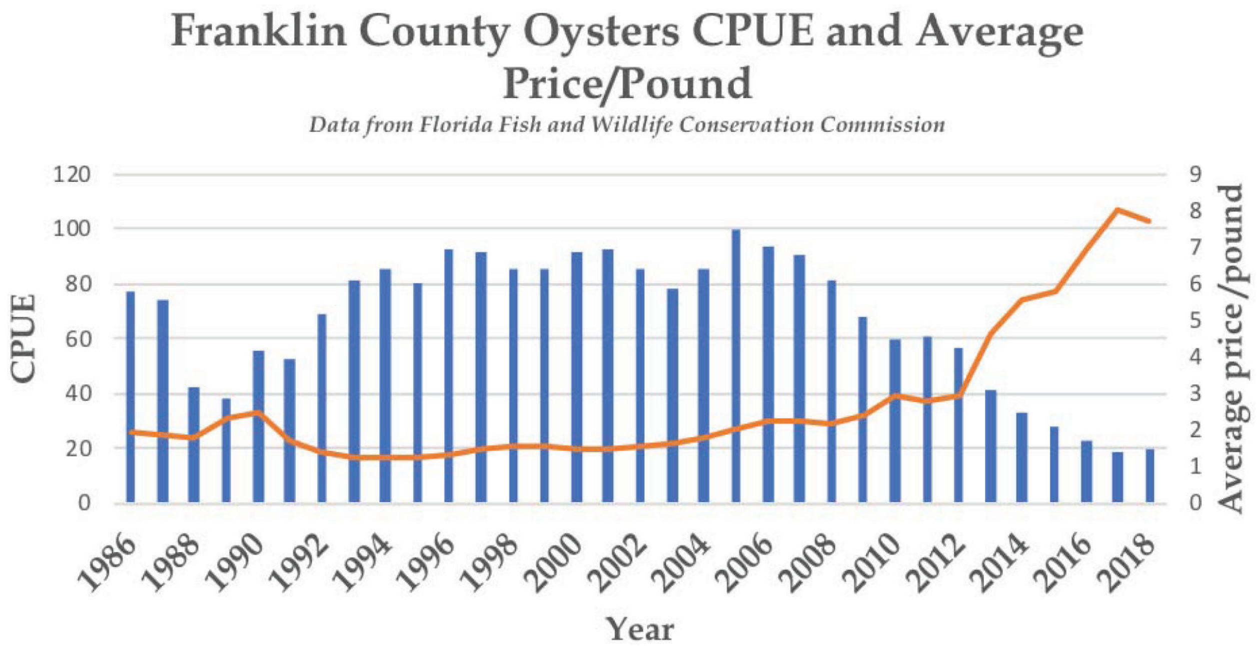

Figure 13. Oysters catch per unit effort and average price per pound of oysters (*Data from Florida Fish and Wildlife Conservation Commission http://myfwc.com/, Figure by Smith (unpublished)).*

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5. Conclusion

Here we discussed two different estuary systems with differences in ecosystem management goals and plans with different ecosystem indicators (TSS and turbidity in Delaware Inland Bays versus salinity in Apalachicola Bay), however both estuaries have few common issues mainly due to increase population and population driven activities (*see* **Table 3**). These issues include frequent eutrophication events, increase pollutants via storm water runoff, agricultural or residential areas, overfishing and habitat alterations. Both estuary systems have some indicators different from each other such as coral reefs and essential fish habitat for Apalachicola Bay versus essential fish habitat or areas that will be open to shellfish harvesting for the Delaware Inland Bays. Major alterations and changes to those fragile ecosystems are mainly due to anthropogenic activities and management goals for both estuaries should be to minimize further changes and mitigate areas already altered.

Although decision and management strategies will be different, each estuary system or watershed, depending on the critical areas of concerns and related activities, solution is dependent upon how we plan our next action. Are we setting our goal for too short term or

Criteria	Delaware Inland Bays, DE	Apalachicola Bay, FL
Characteristics	• Three low flushing interconnected bodies of water (Indian River Bay, Little Assawoman Bay, and Rehoboth Bay). • Watershed - 811 km^2 in Delaware • Average water depth of 1.2 meters • Frequent alteration to waterways?	• River-dominated estuary and lagoon in Florida. • Watershed - 540 km^2 in Alabama, Georgia and Florida • Average water depth of 2 meters • Pristine system?
Oyster Population Status	• Very limited oyster population • Restoration and mitigation are necessary	• Natural oyster population dwindling, not rebounding
Aquaculture Status	• Aquaculture permits have been issued and approval obtained • However, implementation is very slow	• Natural oyster population is declining • Aquaculture is becoming popular
Challenges	• Frequent eutrophication • Increased pollutants from agricultural and residential runoff • Overfishing • Habitat alterations • Increase land uses due to human population and related activities • Human interference of habitat • Very low natural oyster population and recruitment and approval and implementation of aquaculture	• Reduced freshwater input due to drought and upriver usage • Estuary salinity increase • Increased predation • Most common issues are decrease in oyster population, approval of oyster aquaculture

Criteria	Delaware Inland Bays, DE	Apalachicola Bay, FL
Management Practices	• Short-term management practices primarily on nutrient reduction • Many users of the watershed requiring frequent accommodations • Frequent conflict resolution delaying implementation plans	• Long-term management plan focusing on limiting harvesting
Opportunities	• Good oyster growth and survival at designated oyster aquaculture sites are expected. • Potential for clam aquaculture	• Increased oyster culture • Potential for mussel aquaculture

Table 3. Comparison of two estuaries with differences in water quality, anthropogenic impacts, and management goals.

are we having a comprehensive plan? Either it is re-introduced to the area in the case of the Delaware Inland Bays or naturally occurring in Apalachicola Bay, oysters provide ecosystem services long proven and sustainability of these ecosystems lies on the comprehensive and integrated ecosystem planning and assessment. Although integrated ecosystem assessment plan is not available for the Delaware Inland Bays with promising nutrient reduction and waterway improvement initiatives with leadership of the Center for Inland Bays, there are few applied for Apalachicola Bay that provides foundation for assessing the merging needs of the area from the ecosystem health perspectives?

Whether aquaculture is used for revitalizing habitat or restoring native species or human consumption, there are big variation the way each operate. Growing demand for fresh seafood has prompted a long-term viable and sustainable aquaculture industry worldwide. With wild capture fisheries exceeding the maximum sustainable harvest capacity, aquaculture has become a bridge in closing the gap between rising demand and seafood sources. By 2011, farmed seafood accounts over 50% of overall production in the global marketplace [82]. As stated clearly by Shumway et al. [83] "Shellfish are one of the best candidates for ecologically sustainable aquaculture. Farming of shellfish not only provides a high quality, high value, sustainable harvest from the ocean, it also provides jobs and social and economic development, all while providing tangible benefits to the marine environment. A productive shellfish farm means a healthy and equally productive surrounding environment let's give the lowly molluscs their due!"

Restoring oyster population requires further elevation aquaculture has and will enhance the ecosystem health of both watershed discussed in this chapter. Either, we cease wild harvesting or we provide the push to enhance the population and in case of oysters, we are hopeful "aquaculture" will provide both environmental and economical stability in those bays.

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References

[1] Chaillou JC, Weisberg SB, Kutz FW, DeMoss TE, Mangiaracina L, Magnien R, Eskin R, Maxted J, Price K, Summers JK. Assessment of the Ecological Condition of the Delaware and Maryland Coastal Bays. Annapolis, Maryland, USA: U.S. Environmental Protection Agency, Region III; 1994. p. 119

[2] Zimmerman RJ, Minello TJ, Baumer MC, Castiglione M. Oyster Reef as Habitat for Estuarine Macrofauna. Galveston, TX: NOAA Technical Memorandum, NMFS-SEFC-249; 1989. p. 16

[3] Newell RIE. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: A review. Journal of Shellfish Research. 2004;**23**:51-61

[4] Takacs R, King J, Jasinski P. Oyster restoration on the east and gulf coasts. NOAA Habitat Connections. 2005;**5**(2):1-4

[5] Brumbaugh RD, Sorabella LA, Oliveras Garcia C, Goldsborough WJ, Wesson JA. Making a case for community-based oyster restoration: An example from Hampton roads, Virginia, USA. Journal of Shellfish Research. 2000;**19**:467-472

[6] Kennedy VS. The ecological role of the eastern oyster, *Crassostrea virginica*, with remarks on disease. Journal of Shellfish Research. 1996;**15**:177-183

[7] Rothschild BJ, Ault JS, Goulletquer P, Heral M. Decline of the Chesapeake Bay oyster population: A century of habitat destruction and overfishing. Marine Ecology Progress Series. 1994;**111**:29-39

[8] Marenghi FP. Floating oyster (*Crassostrea virginica*) aquaculture as habitat for fishes and macroinvertebrates in Delaware's Inland Bays. Master's Thesis in Natural Resources. Delaware State University: Dover, Delaware, USA; 2009. 203 pp

[9] Goldsborough W, Meritt D. Oyster Gardening for Restoration and Education. Maryland Sea Grant College Program. College Park, Maryland: Oyster Alliance; 2001. p. 12

[10] Luckenbach MW, O'Beirn FX, Taylor J. An Introduction to Culturing Oysters in Virginia. Gloucester Point, Virginia: School of Marine Science Virginia Institute of Marine Science College of William and Mary; 1999. p. 24

[11] Delaware Inland Bays Estuary Program Report (DIBEP). Science and Technical Advisory Committee, Delaware Inland Bays Estuary Program Characterization Summary. Dover, Delaware. 1993

[12] Delaware Center for the Inland Bays Report. Oyster Gardening Program. 2008. http://darc.cms.udel/ibog/index.html [Accessed: April 12, 2017]

[13] Delaware Center for the Inland Bays Report. The Delaware Center for Inland Bays. Report on State of the Delaware Inland Bays. Final Report of the Shellfish Aquaculture Tiger Team to the Board of Directors. 2011. http://www.inlandbays.org/wp-content/documents/2011-state-of-the-bays.pdf [Accessed: April 12, 2015]

[14] Walch M, Seldomridge E, McGowan A, Boswell S, Bason C. 2016 State of the Delaware Inland Bays. Rehoboth Beach, Delaware: The Delaware Center for the Inland Bays, Rehoboth Beach Delaware; 2016. p. 72

[15] Martin DM, Morton T, Dobrzynski T, Valentine B. Estuaries on the Edge: The Vital Link between Land and Sea. Washington, DC: The American Oceans Campaign; 1996. p. 297

[16] U.S. Environmental Protection Agency. 2011. State of the Delaware Inland Bays. https://www.epa.gov/sites/production/files/2015-09/documents/2011-state-of-the-bays.pdf [Accessed: January 17, 2017]

[17] Grabowski JH, Conrad RF, Keeler AG, Opaluch JJ, Peterson CH, Piehler MF, Powers SP, Smyth AR. Economic valuation of ecosystem services provided by oyster reefs. Bioscience. 2012;**62**(10):900-909

[18] Erbland P. A Comparison of the Macrofaunal Communities Inhabiting a Created Oyster (*Crassostrea virginica*) reef and oyster aquaculture gear. Master's Thesis. Delaware State University: Dover, Delaware. 2007. 87 pp

[19] Erbland PJ, Ozbay G. A comparison of the macrofaunal communities inhabiting a *Crassostrea virginica* oyster reef and oyster aquaculture gear in Indian River Bay, Delaware. Journal of Shellfish Research. 2008;**27**:757-768

[20] Marenghi FP, Ozbay G. Floating oyster, *Crassostrea virginica* Gmelin 1791, aquaculture as habitat for fishes and macro-invertebrates in Delaware inland bays: The comparative value of oyster clusters and loose Shell. Journal of Shellfish Research. 2010a;**29**(4):889-904

[21] Marenghi FP, Ozbay G. Preliminary habitat assessment of floating oyster (*Crassostrea virginica*) gardens (Delaware). Restoration Ecology Journal. 2010b;**28**(3):254-257. DOI: 10.3368/er.28.3.254

[22] Marenghi F, Ozbay G, Rossi-Snook K, Chalabala EJ. Restoration programs in inland bays improves ecosystems as oyster populations recover. Global Aquaculture Alliance Global Aquaculture Advocate. 2009:16-17

[23] Reckenbeil BA. Assessment of oyster restoration along human altered shorelines in the Delaware Inland Bays: An examination of riprap stocked with the eastern oyster (*Crassostrea virginica*). Master's Thesis in Natural Resources. Delaware State University: Dover, Delaware, USA; 2013. 189 pp

[24] Rossi-Snook K, Ozbay G, Marenghi F. Oyster (*Crassostrea virginica*) gardening for restoration in Delaware Inland Bays, USA. Aquaculture International Journal. 2009;**18**(1):61-67. DOI: 10.1007/s10499-009-9271-5

[25] Kee E. Delaware Agriculture. 2010. http://www.nass.usda.gov/Statistics_by_State/Delaware/Publications/DE%20Ag%20Brochure_web.pdf [Accessed: January 12, 2015]

[26] Delaware Center for the Inland Bays Report. The Power of People and Nature to Restore the Waters of the Inland Bays. 2015. 8 pp. https://www.inlandbays.org/wp-content/uploads/2-2-2016-CIB-Annual-Report-2015-FINAL.pdf [Accessed: April 22, 2017]

[27] Delaware Center for the Inland Bays Report. New Faces Changing Landscapes. The Delaware Center for Inland Bays: Issues Affecting the Bays. 2014. 8 pp. http://www.inlandbays.orgabout-the-bays [Accessed: April 12, 2015]

[28] Committee on Environment and Natural Resources. 2010. Scientific Assessment of Hypoxia in U.S. Coastal Waters. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology: Washington, DC, 164 pp

[29] Kellogg ML, Cornwell JF, Owens MS, Paynter KT. Denitrification and nutrient assimilation on a restored oyster reef. Marine Ecology Progress Series. 2013;**480**:1-19. DOI: 10.3354/meps10331

[30] Rose JM, Bricker SB, Ferreira JG. Comparative analysis of modeled nitrogen removal by shellfish farms. Marine Pollution Bulletin. 2015;**91**(1):185-190. DOI: 10.1016/j.marpolbul.2014.12.006

[31] DNREC Division of Watershed Stewardship. Shellfish Growing Waters. 2015. http://www.dnrec.delaware.gov/swc/wa/Pages/Shellfish-Growing-Waters.aspx [Accessed: January 12, 2015]

[32] DNREC Division of Fish and Wildlife. Proposed Shellfish Aquaculture Development Areas. 2014. http://www.dnrec.delaware.gov/fw/fisheries/pages/shellfishaquaculture.aspx [Accessed: January 12, 2015]

[33] Livingston RJ. The Ecology of the Apalachicola Bay System: An Estuarine Profile. U.S. Fish and Wildlife Service FW/OBS 82/05; 1984, 148 pp

[34] McNulty JK, Lindall Jr WN, Sykes JE. Cooperative Gulf of Mexico Estuarine Inventory and Study, Florida: Phase I, Area Description. OAA Tech Report. NMFS Circ-368; 1972. 126 pp

[35] Iseri KT, Langbein WB. Large rivers of the United States: U.S. Geological Survey Circular 686; 1974, 10 pp

[36] Light HM, Vincent KR, Darst MR, Price FD. Water-Level Decline in the Apalachicola River, Florida, from 1954 to 2004, and Effects on Floodplain Habitats: U.S. Geological Survey Scientific Investigations Report 2006-5173; 2006. 83 pp

[37] USGS. Coastal and Marine Geology Program. U.S. Geological Survey Open File Report 2006-1381. Geophysical Mapping of Oyster Habitats in a Shallow Estuary; Apalachicola Bay, Florida. 2006. https://cmgds.marine.usgs.gov/publications/of2006-1381/html/maps.htm [Accessed: April 30, 2018]

[38] ***U.S. Department of the Interior, U.S. Geological Survey. USGS current conditions for the nation. USGS 02359170 Apalachicola River NR Sumatra, FL. USGS Sumatra gage. 2018. Website https://waterdata.usgs.gov/nwis/uv?02359170 [Accessed: April 30, 2018]

[39] Florida Sea Grant and University of Florida and authors therein. Apalachicola Bay Oyster Situation Report. 2013. TP-200

[40] NWF National Wildlife Federation (NWF)/Florida Wildlife Federation (FWF). An Unfavorable Tide Global Warming, Coastal Habitats and Sportfishing in Florida; 2006. 60 pp

[41] Havens K, Allen M, Irani T, Lindsey A, Morris JG, Kane A, Kimbro D, Otwell S, Pine B, Walters C. Apalachicola Bay Oyster Situation Report. Florida Sea Grant TP-200: University of Florida; 2013. p. 32

[42] Jones CG, Lawton JH, Shachak M. Organisms as ecosystem engineers. Oikos. 1994;**69**: 373-386

[43] Korringa P. Recent advances in oyster biology. The Quarterly Review of Biology. 1952; **27**(266-308):339-365

[44] Wells HW. The Fauna of oyster beds, with special reference to the salinity factor. Ecological Monographs. 1961;**31**(3):239-266. DOI: 10.2307/1948554. http://www.jstor.org/stable/1948554

[45] Newell RIE. Ecological changes in Chesapeake Bay: Are they the result of overharvesting the American oyster, *Crassostrea virginica?* In: Lynch MP, Krome EC, editors. Understanding the Estuary: Advances in Chesapeake Bay Research. Gloucester Point, Virginia: Chesapeake Research Consortium, Publication 129 CBP/TRS 24/88; 1988. pp. 536-546

[46] Bahr LM, Lanier WP. The Ecology of Intertidal Oyster Reefs of the South Atlantic Coast: A Community Profile. Washington, D.C. FWS/OBS-81/15: U.S. Fish and Wildlife Service, Office of Biological Services; 1981. p. 105

[47] Breitburg DL. Are three-dimensional structure and healthy oyster populations the keys to an ecologically interesting and important fish community? In: Luckenbach MW, Mann R, Wesson JA, editors. Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Gloucester Point, Virginia: VIMS Press; 1998. pp. 239-250

[48] Posey MH, Alphin TD, Powell CM, Townsend E. Oyster reefs as habitat for fish and decapods. In: Luckenbach MW, Mann R, Wesson JA, editors. Oyster Reef Habitat Restoration: A Synopsis of Approaches. Williamsburg, Virginia: Virginia Institute of Marine Science Press; 1999. pp. 229-237

[49] Rodney WS, Paynter KT. Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay in Maryland. Journal of Experimental Marine Biology and Ecology. 2006;**335**:39-51

[50] Piazza BP, Banks PD, LaPeyre MK. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. Restoration Ecology. 2005;**13**:499-506

[51] Kitchell JE, O'Neill RV, Webb D, Gallepp G, Bartell SM, Koonce JF, Ausmus BS. Consumer regulation of nutrient cycling. Bioscience. 1979;**29**:28-34

[52] Malone TC, Kemp WM, Ducklow HW, Boynton WR, Tuttle JH, Jonas RB. Lateral variation in the production and fate of phytoplankton in a partially stratified estuary. Marine Ecology Progress Series. 1986;**32**:149-160

[53] Newell RIE, Fisher TR, Holyoke RR, Cornwell JC. Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay, USA. In: Dame R, Olenin S, editors. The Comparative Roles of Suspension Feeders in Ecosystems. NATO Science Series IV Earth and Environmental Sciences. Netherlands: Springer; 2005. pp. 93-120

[54] Newell RIE, Cornwell JC, Owens MS. Influence of simulated bivalve biodeposition and microphytobenthos on sediment nitrogen dynamics, a laboratory study. Limnology and Oceanography. 2002;**47**:1367-1379

[55] Boucher G, Boucher-Rodoni R. In situ measurement of respiratory metabolism and nitrogen fluxes at the interface of oyster beds. Marine Ecology Progress Series. 1988;**44**:229-238. DOI: 10.3354/meps044229

[56] Dame RF. Oyster refs as complex systems. In: Dame RF, Olenin S, editors. The Comparative Roles of Suspension-Feeders in Ecosystems. Dordrecht, The Netherlands: Kluwer Academic Publishers; 2005. pp. 331-344

[57] Prins TC, Smaal AC, Dame RF. A review of the feedbacks between bivalve grazing and ecosystem processes. Aquatic Ecology. 1998;**31**(4):349-359

[58] Jackson AR, Rouse DR, Ozbay G. The effects of oyster (*Crassostrea virginica*) structure and bioactivity on water quality, sediment nutrients, Infaunal communities, and transient fish biomass. Journal of Environmental Monitoring and Restoration. 2008;**4**:66-82

[59] Fuoco M. Nitrogen source tracking and benthic community assessment in relation to oyster aquaculture in the Delaware inland bays. Master's Thesis in Natural Resources. Delaware State University: Dover, Delaware, USA; 2018. 71 pp

[60] Ulanowicz RE, Tuttle JH. The trophic consequences of oyster stock rehabilitation in Chesapeake Bay. Estuaries. 1992;**15**:298-306

[61] Marenghi F, Ozbay G, Erbland P, Rossi-Snook K. A comparison of the habitat value of sub-tidal and floating oyster (*Crassostrea virginica*) aquaculture gear with a created reef in Delaware's inland bays, USA. Aquaculture International Journal. 2009b;**18**:69-81. DOI: 10.1007/s10499-009-9273-3

[62] Ozbay G, Reckenbeil B, Marenghi F, Erbland P. Eastern oyster (*Crassostrea virginica*) aquaculture and diversity of associated species. In: Turner JP, editor. Oysters: Biology, Consumption, and Ecological Importance. NOVA Publishing. Book Chapter; 2013. p. 128. ISBN: 978-1-62948-808-0

[63] Ozbay G, Marenghi F, Rossi-Snook K, Ewart J, Chalabala EJ. 2009. Delaware Oyster Gardening and Restoration - A Cooperative Effort. YSI Application Note. YSI Aquaculture 0409 A571. 2009 YSI Inc. 3 pp

[64] Delaware Center for the Inland Bays Report. Oyster (*Crassostrea virginica*) Gardening Program for Restoration in Delaware's Inland Bays, USA. 2013. https://www.researchgate.

net/publication/226882567_Oyster_Crassostrea_virginica_gardening_program_for_restoration_in_Delaware's_Inland_Bays_USA [Accessed: April 22, 2017]

[65] Fulford RS, Breitburg DL, Newell RIE, Kemp WM, Luckenbach M. Effects of oyster population restoration strategies on phytoplankton biomass in Chesapeake Bay: A flexible modeling approach. Marine Ecology Progress Series. 2007;**336**:43-61. DOI: 10. 3354/meps336043

[66] Pomeroy LR, D'Elia CF, Schaffner LC. Limits to top-down control of phytoplankton by oysters in Chesapeake Bay. Marine Ecology Progress Series. 2006;**325**:301-309. DOI: 10.3354/meps325301

[67] Buitrago E, Alvarado D. A highly efficient oyster spat collector made with recycled materials. Aquaculture Engineering. 2005;**33**:63-72

[68] Ozbay G, Cannon A. Gauging benefits of oyster garden restoration in Delaware. World Aquaculture Society. 2017;**48**(4):59-61

[69] Edmiston HL. A River Meets the Bay: A Characterization of the Apalachicola River and Bay system. Apalachicola National Estuarine Research Reserve (ANERR). ANERR National Estuarine Research Reserve 2014. 2008. http://www.nerrs.noaa.gov/Apalachicola/welcome.html [Accessed: April 12, 2018]

[70] Galtsoff PS. The American oyster *Crassostrea virginica* Gmelin. Fisheries Bulletin. 1964;**64**: 1-480

[71] FDEP. Apalachicola-Chattahoochee-Flint River System. 2017. http://www.dep.state.fl.us/mainpage/acf/timeline.htm [Accessed: January 12, 2015]

[72] Chanton J, Lewis FG. Examination of coupling between primary and secondary production in a river-dominated estuary: Apalachicola Bay, Florida, U. S. A. Limnology and Oceanography. 2002;**47**:683-697

[73] Livingston RJ, Lewis III FG, Woodsum GC, Niu X, Howell IV RL, Ray GL. Modeling oyster population response to variation in freshwater input. Estuarine, Coastal and Shelf Science. 2000;**50**:655-672

[74] Livingston RJ, Iverson RL, Estabrook RH, Keys VE, Taylor Jr J. Major features of the Apala chicola Bay system: Physiography, biota, and resource management. Florida Scientist. 1974;**4**:245-271

[75] Childs CR, Rabalais NN, Turner RE, Proctor LM. Erratum: Sediment denitrification in the Gulf of Mexico zone of hypoxia: Marine Ecology Progress Series 247; Cambria. pp. 310-310

[76] Mortazavi B, Iverson RL, Landing WM, Lewis FG, Huang WR. Control of phytoplankton production and biomass in a river-dominated estuary: Apalachicola Bay, Florida, USA. Marine Ecology Progress Series. 2000a;**198**:19-31

[77] Mortazavi B, Iverson RL, Huang WR, Lewis FG, Caffrey J. Nitrogen budget of Apalachicola Bay, a bar-built estuary in the northeastern Gulf of Mexico. Marine Ecological Progress Series. 2000b;**195**:1-14

[78] Alderstein D. State to Expand Aquaculture Leases. The Apalachicola and Carrabelle Times. 2018. Online. http://www.apalachtimes.com/news/20180405/state-to-expand-aquaculture-leases [Accessed: on April 22, 2018]

[79] California Aquaculture Association. NOAA Releases Fisheries of the United States, 2016 Report. 2017. October 30, 2017. Chico, CA 95928 info@caaquaculture.org. http://caaquaculture.org/2017/10/30/noaa-releases-fisheries-of-the-united-states-2016-report/[Accessed: April 26, 2018]

[80] NOAA Fisheries-Office of Aquaculture. Shellfish Aquaculture: How Much Is U.S. Shellfish Aquaculture Worth? Report by December 4, 2017. 2017. https://www.fisheries.noaa.gov/insight/shellfish-aquaculture. [Accessed: May 18, 2018]

[81] Stewart J. Entrepreneur-driven US oyster industry growing on farm-to-table movement. Undercurrent News, January 27, 2014. 2014. https://www.undercurrentnews.com/2014/01/27/entrepreneur-driven-us-oyster-industry-growing-on-farm-to-table-movement/ [Accessed: May 20, 2018]

[82] Bush SR, Toonen H, Oosterveer P, Mol AP. The 'devils triangle' of MSC certification: Balancing credibility, accessibility and continuous improvement. Marine Policy. 2013;**37**: 288-293. DOI: 10.1016/j.marpol.2012.05.011

[83] Shumway SE, Davis C, Downey R, Karney R, Kraeuter JParsons J, Rheault R, Wikfors G. Shellfish aquaculture: In praise of sustainable economies and environments. World Aquaculture. 2003;**34**:15-18

[84] Ozbay G, Phalen L. A Comparison of Bottom, Hanging, and Floating Gear for Growing Eastern Oysters (Crassostrea virginica) in Broadkill River. Delaware Oyster Aquaculture Technical Paper 1. Dover, DE: Delaware State University; 2017. pp. 6

[85] NOAA declares fishery disaster for Apalachicola oysters. http://blog.al.com/gulf-coast/2013/08/noaa_declares_fishery_disaster.html [Accessed on June 25, 2018]

[86] Tagliapietra D, Sigovini M. Benthic fauna: Collection and identification of macrobenthic invertebrates. NEAR Curriculum in Natura Environmental Science, Terre et Environnement. 2010;**88**:253-261. ISBN: 2-940153-87-6