LONG ISLAND SOUND HABITAT RESTORATION INITIATIVE

SECTION 7: NATURAL SHELLFISH BEDS

(Version 1.0, August 2018)

Technical Support For Coastal Habitat Restoration

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TABLE OF CONTENTS

NATURAL SHELLFISH BEDS

Description

Natural shellfish beds are a prominent feature of the benthic environment. The terms 'bed' and 'reef' are used to describe the three-dimensional habitat that is formed by accumulations of filter-feeding bivalve mollusks and their shells. In Long Island Sound, the predominant habitat-forming shellfish species include the eastern oyster (*Crassostrea virginica*), the ribbed mussel (*Guekensia demissa*), the blue mussel (*Mytilus edulis*) and the northern horse mussel (*Modiolus modiolus*).

The native oyster is the most common of the habitat-forming species. In the Long Island Sound, the location of natural oyster beds is, in most cases, close to shore and near to the mouths of its many tidal rivers. Intertidal beds tend to be seasonal in nature and less structurally complex than subtidal beds (Fig. 1). The eastern oyster tolerates a wide range in environmental conditions including temperature, dissolved oxygen, and salinity (Shumway 1996). Spawning occurs in late summer as water temperatures approach 16 degrees Celsius in Long Island Sound (Loosanoff 1966, Loosanoff 1969). Eastern oysters are extremely fecund, producing millions of eggs per spawning cycle (Galtsoff 1930). Fertilized eggs transform into larvae within a day and then remain in the water column for up to three weeks (Fig. 2). Most oysters are protandric, beginning their lives as males and then transform to females within a year or two (Galtsoff 1964). Oysters require firm bottom or substrate such as rock, shell commonly called 'cultch', or any other hard surface to form a reef. As the oyster settles, it attaches the left valve to the substrate with a substance produced by the byssus gland and is then called "spat" or "set". Growth rate is highly dependent upon temperature and food availability (Kennedy 1996). Oysters can reach harvest size (76-90 mm) in 4-5 years in Long Island Sound (Shumway 1996), and they may live 20 years or longer (Buroker 1983).

Three species of native mussels can be found in Long Island Sound. Mussels form large aggregations using byssal fibers to attach themselves to each other and other hard surfaces. Unlike oysters, mussels are able to reattach if dislodged from the original substrate. The most common species, the blue mussel, *Mytilus edulis*, forms extensive subtidal beds, though some intertidal beds exist. The species spawns in Long Island Sound in spring, though secondary fall and winter spawning events may occur (Brousseau 1983, Newell et al. 1982, Sunila et al. 2004). The blue mussel has separate sexes, and, similar to native oysters, the eggs are fertilized externally and become planktonic larvae. The larval development stage may extend up to 35 days after which the mussels settle to the benthic environment, and their lifespan is generally 11-12 years (Newell 1989).

The abundance and distribution of blue mussels in the LIS has not been well-documented, making it difficult to assess trends in either NY or CT. As a result, there is limited knowledge on how these beds have fluctuated over time, and no direction on how to assess the health of these shellfish beds. According to the New York State Department of Environmental Conservation (NYSDEC) (2005), while there was never a large commercial fishery in New York, blue mussel harvest has decreased in recent years, most likely due to a change in harvest pressure.

The northern horse mussel, *Modiolus,* inhabits deeper waters of the Sound and is much less common than the aforementioned species. Kent et al. (2017) note that *M. modiolus* is a priority for habitat conservation in the northeast Atlantic, however, because of the lack of information on the abundance and distribution of this species and commercial fishery interests in Long Island Sound, it has not been identified as a target for restoration.

The ribbed mussel, *Geukensia demissa*, is commonly found along the fringes of salt marshes where it occupies a niche habitat embedded in the peat, attached to other mussels, and *Spartina* spp. plants (Fig. 3). It can occur at densities exceeding 1000 individuals per square meter (Dreyer and Niering 1995). These animals are dioecious and have been observed to spawn during the summer months (Brousseau 1982). The life cycle of *Geukensia* is similar to that of *Mytilus* and *Modiolus.* Aside from documentation of their presence within Long Island Sound tidal wetlands (see Long Island Sound Habitat Restoration Initiative Technical Support for Habitat Restoration 2003, Section 1), there is little mention of the extent of ribbed mussel populations in the historical literature. This is likely due to the fact that no major commercial or recreational fishery has ever existed.

The remainder of this chapter will focus primarily on natural oyster beds, their historic and current status, and restoration.

Important Environmental Conditions

The size and distribution of natural shellfish beds are highly dependent upon the species and environmental conditions. The primary factors influencing the formation of shellfish beds include temperature, salinity, nutrients, turbidity, current, and substrate. Oysters in particular are able to adapt to a wide range of environmental conditions which makes them ideal candidates for restoration and enhancement efforts. One caveat is that oysters prefer hard bottom, stable mud surfaces, or areas already colonized by oysters (Galtsoff 1964).

The oyster beds of the Long Island Sound are often subject to a harsher climate than other large U.S. estuaries (e.g. Chesapeake), and the local environmental conditions should be considered in the planning and assessment of shellfish restoration efforts. The intertidal and shallow subtidal reefs in Long Island Sound tend to be ephemeral in nature. While oysters are adapted to harsh climates, tidal exposure to extreme temperatures, wind, waves, and shifting ice can affect survival, growth, and reproduction. Anecdotal accounts by oystermen claimed that Long Island Sound oyster beds never broke the surface due to the scouring of ice in winter months (Visel 2014). Even subtidal areas can be impacted by severe storms, as sand and mud can smother the beds. Shellfish beds are also vulnerable to predation, disease, harmful algae, fishing pressure, water quality impairments, and development.

Coastal ocean acidification is an emerging threat to marine life. Recent research has demonstrated that increasing carbon dioxide in the water column has an effect on shell formation in early life stages of some bivalves (Green et al. 2004, Waldbusser et al. 2010), as well as on metabolic rates of bivalves at various life stages (Waldbusser et al. 2015). Though these early studies have shown deleterious effects on certain species of bivalves, the level and intensity of impacts on other species is relatively unknown. Daily changes in pH are large and routine in estuaries, and bivalves have adapted over time to these conditions. Researchers and coastal managers are working to measure indicators of changing conditions and better understand the potential effects on bivalve shellfish locally and regionally (Northeast Coastal Ocean Acidification Network website http://necan.org).

Value and Functions

Habitat-forming shellfish and the beds they create are part of a healthy and diverse Long Island Sound and play a role in improving impaired estuarine environments. Shellfish reefs provide a host of ecosystems services including the provision of habitat and food, water filtration, coastal erosion control, commercial fisheries, and recreation (Coen et al. 2007, Grabowski and Peterson 2007)

Shellfish beds serve as habitat for a myriad of resident and migratory fish, birds, and invertebrates, and oyster reefs in particular support significantly more and diverse species as compared to non-reef habitats (Wells 1961). Numerous fish and invertebrate species have been observed utilizing Long Island Sound shellfish beds as habitat (Auster et al. 1995, Stewart 1972). These include numerous species managed by the Atlantic States Marine Fisheries Commission (Table 1). In addition to recreationally and commercially important finfish, many other species, e.g. crustaceans, polychaetes, birds, use shellfish reefs as habitat or foraging grounds for one or more of their life stages.

Filter-feeding bivalves have a tremendous capacity to process large volumes of water. Oysters in particular have high filtration or clearance rates, though these rates are dependent on a variety of factors including size, temperature, salinity, food size and concentration and flow rates (Shumway 1996, Riisgård 2001). As they feed, bivalves remove inorganic particulate matter (e.g. suspended solids) and organic particulate matter (e.g. phytoplankton) from the water and play a role in cycling nutrients in the water column and improving water clarity and quality. Because of their complex, three-dimensional structure, oyster reefs can reduce the flow and direction of water, thereby processing nutrients at a high rate (Dame et al. 1984). This is an especially important ecosystem service as excessive nitrogen and other pollutants from land-based human activities have degraded coastal water quality, impacting marine habitats and animals in Long Island Sound.

Farmed shellfish can also provide similar ecosystem services. Nutrients, such as nitrogen and phosphorus, are often found in excess in our coastal waters due to the overuse of fertilizers on lawns and farms. Nutrient 'bioextraction' is the practice of farming and harvesting shellfish (or seaweed) for the purpose of removing nitrogen and other nutrients from natural water bodies (EPA Long Island Sound Study http://longislandsoundstudy.net/). This nutrient removal service can be quantified using computerized ecosystem models (Ferreira et al. 2011), and the overall value of shellfish harvest has recently been assessed in the Long Island Sound (Bricker et al. 2015).

Intact shellfish reefs naturally provide some protection against the effects of severe storm events. Nearshore fringing reefs can reflect or reduce wave energy and have been shown to stabilize the shoreline thereby reducing erosion (Meyer et al. 1997). This action can protect and support the growth of critical habitats such as tidal marshes and submerged aquatic vegetation (e.g. eelgrass) beds. While the protection reefs provide should not be overstated, research has shown that recreating oyster reefs to serve as natural breakwaters can measurably mitigate shoreline retreat (Scyphers et al. 2011, La Peyre et al. 2015).

Finally, oysters and other shellfish support important recreational and commercial fisheries in the Long Island Sound. Commercial shellfishing generated greater than $30 million dollars in sales in CT in 2016 (Connecticut Department of Agriculture, Bureau of Aquaculture). The industry provided 359 jobs statewide in 2015 (Lopez et al. 2017), and permit sales for recreational fisheries average approximately $110,000 per year with a multiplier effect exceeding $2 million dollars to the local economy (Pomeroy et al. 2017). In New York, including outside of LIS, commercial shellfisheries were valued at greater than $10 million dollars in 2016 (New York State Department of Environmental Conservation) and while economic data are unavailable, recreational shellfishing is a popular activity in several Long Island townships.

Status and Trends

Pre- and Early European colonization

Historically, natural oyster beds were widespread along the coastlines of Connecticut and New York. Port Jefferson was the most eastern point on the north shore of Long Island where suitable habitat for oysters existed (Ingersoll 1881). In Connecticut, though oysters were found along the entire coast, large natural beds existed in every harbor westward of the Thames River in New London (Ingersoll 1881). In his account of the history of oystering, MacKenzie (1996) identified the eight greatest U.S. and Canadian oyster estuaries, New Haven Harbor, Connecticut being among them.

In pre-Columbian times, Native American women harvested the oysters and prepared them for eating or preserved them for winter use (Ingersoll 1881). Shell piles or ‘middens’ as they are called are the indicators of Native American use of oysters and other bivalves. Lightfoot (1986) describes shellfish exploitation by Native Americans on the north shore of Long Island and in New York City by the numerous shell piles found along the shore. In Connecticut, middens have been identified along the banks of the Quinnipiac River, Housatonic River, Milford Point and Harbor, Connecticut River, Mago Point in Waterford, and at Harrison’s Landing and Mamacoke Cove in the Thames River, and in the Pawcatuck River, as well as sites far inland (Praus 1942; Bellantoni and Dor 1985, Juli and Dreyer 1992, Trapp and Brockett 1999). Evidence of stratigraphic differences in oyster size recovered from midden sites suggests that extensive harvesting was occurring well ahead of European colonization (Bellantoni and Harty 2001).

One of the first European accounts of the extensive oyster beds in the New World was documented when Henry Hudson sailed into New York Harbor in 1609. As he traversed the harbor and into the river that now bears his name, he purchased oysters from the native Lenape who met him in canoes (Juet 2006). Likewise, when the first settlers came to New Haven in 1638, they observed natives eating oysters from the vast natural beds of the Quinnipiac and other nearby rivers (Galpin 1989). Europeans were familiar with oysters, and the natural beds were readily exploited. While an important food source for natives and early coastal colonists, oysters were also highly prized for fertilizer and the soil acidity-reducing nature of the shells. Archeologists have found oyster shell distributed over 18th-century farm sites, and for colonial farmers the shellfish were much more valuable in their fields than on their tables (Bellantoni & Harty 2001). Over time, laws were established to protect natural beds, but not all beds were protected equally and eventually some were designated for private use. Soon after shellfishing began as an industry in Connecticut the nearshore natural beds were being rapidly depleted (Ingersoll 1881).

Prior to 1784 there were no restrictions on the Long Island Sound oyster fishery. In that year the General Assembly of the State of Connecticut passed '*An Act for Encouraging and Regulating Fisheries'* which enabled towns to regulate the harvest of clams and oysters (Anonymous 1784). This early regulation did little to reduce the impact of harvesting on the natural oyster beds (Sweet 1941), but legislation over the next century would go further to protect the natural beds and sustain the fishery.

In the middle of the nineteenth century when the oyster fishery on the coast of France was on the verge of failing, the French government sent an individual to report on the condition of the oysters and the oyster fishery in the United States. De Broca (1876) claimed, "The American oyster…were it not for the constant fisheries, would form reefs, modify currents, obstruct channels - in a word, interfere greatly with navigation." Blackford (1885a) reported that within a decade the natural oyster areas Long Island Sound were in "bad condition" and greatly reduced in size than the previous decade. He noted that most of the natural areas of New York were harvested until they were entirely depleted, and that the beds near Staten Island and City Island "suffered more than the others from the direct action of the refuse materials thrown into the waters" from surrounding cities. The local oyster supply became so scarce that oystermen from Long Island Sound and other northern estuaries began transplanting large quantities of seed and market size oysters from the Chesapeake (Ingersoll 1881).

Though some of the natural beds in Long Island Sound and New York Harbor were completely depleted, nearly 6,000 acres of natural beds were preserved, mainly in Connecticut waters and in a few towns on Long Island (Blackford 1855a, Kellogg 1910). This was chiefly a result of the early protections in place to regulate harvest on the natural beds, and subsequent legislation that allowed cultivation on private beds (Collins 1891, Blackford 1885a). In contrast, the seemingly inexhaustible oyster beds of the Chesapeake and New York Harbor fell victim to the effects of limited restrictions or enforcement (Winslow 1881, Blackford 1885a, Collins 1891).

Connecticut was the first state to grant vested rights in oyster grounds. In 1855, the legislature passed "An Act regulating and protecting the planting of oysters", commonly called the 'Two Acre Law,' which gave towns the ability to grant up to two acres of underwater land (where there was no natural growth of shellfish) for individuals to cultivate oysters or other shellfish (Anonymous 1855). Connecticut's natural oyster beds supported a robust fishery during this time; however, while the intent of the law was to protect the natural grounds from being privatized, a later amendment exempted the towns of Orange, New Haven, and East Haven, and harvesters quickly obtained rights to areas previously identified as natural beds. To make matters worse, many individuals evaded the law and convinced others to secure acreage for them, resulting in large single holdings of shellfish grounds (Sweet 1941). The near shore areas were the focus of the fishing pressure until oystermen learned that they could catch a set of oysters by planting shell or 'cultch', and within a decade there were many lots in the deeper waters, 20 to 30 feet or more, used for planting seed (Collins 1891). These were not areas known to be natural oyster beds.

In 1881 the Connecticut legislature approved an act that established The Shell-fish Commission, a state organization tasked with the designation of oyster grounds in state waters. This was an important move towards better managing the state's shellfish resources. The law called for the waters of Long Island Sound to be surveyed by the U.S. Coast and Geodetic Survey. The Commission identified the boundary between Connecticut and New York and established a line separating the state and town waters (Figure 4). The Commission was given exclusive jurisdiction over the offshore shellfish grounds. In addition, the Commission was given the authority to grant and tax shellfish grounds called 'perpetual franchises' and required to prepare an annual report indicating the location and condition of natural and private shellfish beds (Pike et al. 1882). The Shell Fish Commission mapped the natural and cultivated beds which afforded regulators information to enforce the regulations and protections in place for those areas (Figures 5a-b). According to the Connecticut Bureau of Labor Statistics, the state allowed the privatization of a significant portion of the natural oyster beds, but it reserved large areas for public use (Hotchkiss 1890). The natural beds in some towns (e.g. Greenwich) were and still are covered with private beds, whereas in other towns (e.g. Westport), private beds have been reverted back to natural beds in recent court decisions (Connecticut Department of Energy and Environmental Protection 2004). The natural beds currently under state jurisdiction included a total of 5,805 acres, and in town waters comprised 13,503 acres (Table 2). Descriptions of these beds, as defined by the Superior Court, were documented in Section 2328 and Section 2326 of the Connecticut General Statutes of 1888. The first formal survey of New York oyster beds, which included all of the state's estuaries, documented over 15,586 acres in state waters and estimated 20,000 acres in town waters (Table 3) (Blackford 1885b). In his report to the State, Blackford suggested that New York follow suit with Connecticut and preserve the natural beds.

The Last Century

Oyster production increased dramatically and peaked in the late 19th century only to be followed by decades of decline. During this time, the waters of the Long Island Sound and New York Harbor became a dumping ground, regardless of any restrictions to the contrary. Population growth and industrialization took its toll on the natural beds. Factories disposed manufacturing waste directly into the water (Anderson 2004), while storm sewers and open trenches allowed the flow of human and animal waste into coastal waters (Rowe 1919). Foodborne illness was frequent with cholera and typhoid epidemics killing thousands. Contaminated oysters were the culprits and states scrambled to address the public health concern. The Pure Food and Drug Act of 1906 required new sanitation measures and inspection of food products, but the damage had been done. Oystering was prohibited in many areas, and decreasing demand and prices caused a collapse of the industry.

In the decades that followed, severe storms, abnormal rainfall, drought, extreme temperatures, the construction of wharves, roads, bridges and railways, and predation by starfish and drills took their toll on the remaining natural beds (Sweet 1941, MacKenzie Jr. 1996). The beds did not produce reliable sets of seed again until the 1980s and 1990s when the State of Connecticut and a private company got involved in restoration. As a result of a recommendation of the Connecticut Aquaculture Commission in its 1986 report, a law was established that allowed the state to invest millions of dollars to rehabilitate the (public) natural beds. Over 3,000 acres of State beds were replenished with approximately 5.2 million bushels of shells. The enhancement effort resulted in an exponential rise in production in subsequent years (Connecticut Department of Agriculture, Bureau of Aquaculture). Production increased until 1997 when two parasitic oyster diseases, MSX (causative agent *Haplosporidium nelsoni*) and Dermo (causative agent *Perkinsus marinus*) destroyed nearly 90% of the oyster population (Connecticut Department of Agriculture, Bureau of Aquaculture). Since that time, oyster production has grown steadily in Connecticut, with relatively low and variable production in New York.

Present Day Distribution

Oyster populations are now in peril in many places around the globe. In their examination of the condition of oyster reefs, Beck et al. (2011) concluded that, while oysters are present in most locations examined worldwide, many reefs that were once common are now rare or extinct. In 2005, due to increasing concern about the status of the eastern oyster, the U.S. National Marine Fisheries Service (NMFS) entertained a petition to list the species as threatened or endangered under the Endangered Species Act. A team of experts conducted a status review of the oyster throughout its range and determined "the long-term persistence of eastern oysters throughout their range is not at risk now or in the foreseeable future" (Eastern Oyster Biological Review Team, 2007). While the species was *not* listed as threatened or endangered, the team concluded that restoration is necessary to sustain populations in some locations (e.g. mid- and south Atlantic), while in other locations (e.g. Long Island Sound) restoration is considered important to maintain the fishery and to conserve ecosystem services.

zu Ermgassen et al. (2012) reported the historic extent of oyster populations in Long Island Sound at between 5,001 and 15,000 hectares (12,358 to 37,066 acres) at the time when the resource was already exploited. They noted that because of the extensive leasing of shellfish beds, they have likely underestimated the overall native oyster populations. The only certainty is that current populations do not reflect historic oyster populations in the Long Island Sound.

The largest and most important natural beds in Connecticut were protected for public use and designated as such in Superior Court. The use of the term "natural bed" to define these areas has often been the source of confusion because the term "natural" is typically thought of as referring to a wild population that is protected from harvest. That said, there have for many years been restrictions in place to prevent the overharvest of oysters from these areas, and the populations there sustained the oyster farming industry for more than a century. The current extent of these designated natural shellfish beds includes 5,327 acres in state waters and 16,589 in town waters (Table 4). Though the location and condition of unharvested natural beds are not well known, efforts are being made to identify and map those that are the most ecologically important (David Carey, Connecticut Department of Agriculture/Bureau of Aquaculture, personal communication April 2 2018). There are anecdotal reports of small beds (1-10 acres) in town waters, but as these areas have not been formally surveyed, it is impossible to report on their status.

In New York Harbor, the once thriving native oyster population and oyster reefs are referred to as 'functionally extinct' meaning that more than 99% of the population has been lost and the remaining system provides little to no ecosystem value (Beck et al. 2011). The fate of New York's natural beds in Long Island Sound waters is lesser known. The oyster beds of New York were not protected in the same manner as they were in Connecticut and no recent statewide population assessments have been conducted (Melissa Albino, New York State Department of Environmental Conservation, personal communication April 7 2018).

Given their ecological, economic, and cultural importance, restoration of oyster beds is a priority in both states. The Long Island Sound Comprehensive Conservation and Management Plan (Anonymous 2015) and the Connecticut Shellfish Vision Plan (Anonymous 2016) identified the need to increase shellfish populations for maintaining and growing the fisheries industries and conserving ecosystem services. Shellfish restoration efforts in Connecticut are limited, though interest exists. The oyster industry continues to rely primarily upon seed sourced from designated natural beds. Because of the economic importance of the oyster industry, the rehabilitation of these beds is a priority. Additionally, there is interest in re-establishing and creating shellfish beds to restore ecosystem function. Ribbed mussels have been considered a candidate species for nutrient removal from eutrophic Long Island Sound waters. Galimany et al. (2013) grew mussels at two Long Island Sound sites and suggested that this species may be a good candidate based upon its wide environmental tolerance and lack of commercial or recreational harvest. A number of small-scale municipal projects have been established mainly for fishery enhancement efforts.

New York has dedicated funding and government support for restoration project planning and implementation. In 2017 New York State Governor Andrew Cuomo announced a $10.4 million investment to restore the Long Island shellfish stocks and established a Shellfish Restoration Council to guide plans to seed oysters and clams in five estuaries (Restore New York Shellfish https://www.dec.ny.gov/outdoor/110939.html). Also, the Billion Oyster Project, a non-profit organization created to restore oyster reefs and repopulate oysters in New York City waters, has plans to restore one billion oysters to New York Harbor by 2030, with a number of projects on-going throughout the state. The New York/New Jersey Baykeeper, an environmental non-profit group based in New Jersey, established a 1-acre oyster reef at Soundview Park in the Bronx River, as well as another site at the Naval Weapons Station Earle in Raritan Bay. Baykeeper has restored 7 million oysters back to New York Harbor waters with 200,000 – 500,000 new oysters introduced annually (New York/New Jersey Baykeeper http://nynjbaykeeper.org/resources-programs/restoration/). Other non-profit groups are leading smaller municipal projects.

Regulations Governing Natural Shellfish Beds and Shellfish Restoration Efforts

The State Department of Agriculture, Bureau of Aquaculture currently manages the state waters of Connecticut, and the town waters (north of the jurisdiction line) are managed by municipal shellfish commissions in each coastal town. The Department of Environmental Conservation manages the shellfish areas to the south of the state jurisdiction line in New York. The regulations in place since the late 1800s still serve to protect designated natural shellfish beds in Connecticut.

Wildlife restoration, including shellfish restoration projects, is managed under the authority of a number of state and federal agencies, and typically in collaboration with local authorities. Typically, projects involve permission to use and develop the physical space for the activity, as well as permits to place fill (e.g. shell or other substrate, broodstock, remote set oysters) or structures (e.g. bags containing shell and/or shellfish, spat collecting gear). Projects that involve the import of shellfish larvae, seed, adults, or shell require an additional license. In Connecticut, the process involves the Department of Agriculture, Bureau of Aquaculture, the Department of Energy and Environmental Protection (the coastal zone management agency), the U.S. Army Corps of Engineers, and the town where the project will take place. In New York, projects are routed through the Department of Environmental Conservation Division of Environmental Permits (the coastal zone management agency), the New York State Department of State, the U.S. Army Corps of Engineers, and the town where the project will take place.

Restoration Objectives and Methods

Restoration is an umbrella term that includes enhancement, creation, and re-establishment of natural shellfish habitat. The Eastern Oyster Biological Review Team (2007) developed the following definitions to help define the type of restoration method:

1. Re-establishment: construction of habitat where it once historically or formerly existed
2. Enhancement: manipulation of the physical, chemical, or biological characteristics of a site to heighten, intensify, or improve specific function(s). Enhancement results in a change in function, but not a change in acreage.
3. Creation: manipulation of the physical, chemical, or biological characteristics to develop oyster habitat where it did not previously exist.

There are several restoration methods that include:

1. prohibition of fishing effort on an existing bed (sanctuary);
2. reduction of fishing effort on existing bed;
3. construction of subtidal reef (to create habitat);
4. construction of intertidal reef (to create habitat);
5. placement of shell/cultch (to encourage recruitment);
6. placement of broodstock (to increase reproductive capacity); and
7. placement of remotely set oysters (a technique for producing oyster seed from larvae and setting them on clusters of shell).

The aforementioned methods can achieve one or more of the following restoration objectives:

1. improving water quality;
2. improving fish and wildlife habitat;
3. improving shoreline stabilization and erosion control; and
4. improving capture fisheries.

Proper site selection is the key to any restoration effort. There are a number of factors to consider, depending upon the project purpose:

1. Did the area historically support shellfish populations?
2. Does the area currently support shellfish populations?
3. Is there firm, stable substrate at the site?
4. Is there larval recruitment to the site?
5. What is the velocity and direction of the current?
6. Is there sediment movement along the bottom? If so, what is the deposition rate?
7. What is the water classification? Does the town/state allow construction in this area?

Baggett et al. (2014) recommend collecting other ancillary data to help identify problems with a restoration site including:

1. presence of predatory, pest, and/or competitive species;
2. disease prevalence and intensity;
3. oyster condition index (a measure of health);
4. gonad development (a measure of reproductive status);
5. sex ratio (ratio of male to female oysters);
6. shell volume; and,
7. percent cover of reef substrate.

Additionally, the USDA Natural Resources Conservation Service recommends identifying the soil type (Debbie Surabian, personal communication).

Well-planned and implemented restoration efforts can provide many ecological, economic and social benefits, however, there are risks inherent in any project. This section identifies key recommendations to prevent or minimize the potential risk associated with restoration efforts.

1. <u>Use local, native shellfish</u>. Evidence has shown that the intentional or accidental release of non-indigenous species can have enormous environmental and economic consequences (Carlton 2001). The introduction of non-native shellfish or shells has been shown to be a vector for invasive species, and responsible for the spread of pests, parasites, and diseases (Mann 1983, Naylor et al. 2001, Ruesink et al. 2005, Cohen and Zabin 2009). There are genetic differences among geographically separated populations, and growth, reproductive success, and disease susceptibility of these populations differ as a result. Therefore, local strains should be used as they are adapted to local environmental conditions and typically perform better in their native geographic range. It is also extremely important to maintain genetic diversity when implementing restoration efforts. Aside from using locally collected brood stock, it is important to use pair-wise crossings of these animals when spawning.

2. <u>Use clean shell or substrate that has been under quarantine.</u> Oyster shell, or the shells of other bivalves are used as substrate or for stocking seed using remote setting techniques; however, the shell itself may pose threats similar to the use of live shellfish. Research has shown that a shell quarantine of a month or longer can significantly reduce the risk of shellfish disease transfer (Bushek et al. 2004). Most states have adopted a policy requiring a quarantine period of six months or longer.

3. <u>Consider existing user groups</u>. Learn how the area is used at various times of the year. Avoid construction projects in heavily used recreational and commercial areas.

4. <u>Consider potential human health risks</u>. Natural shellfish beds are often found nearshore in areas receiving high inputs of point source and non-point source pollution. These areas may be closed to shellfishing and harvest prohibited due to the human health risks. Restoration is discouraged in areas classified as “Prohibited” unless there is adequate enforcement of the area.

5. <u>Obtain all necessary licenses and permits</u>.

6. <u>Abide by local, state, and federal laws and policies.</u>

Restoration Success and Monitoring

There are specific metrics that should be monitored for every shellfish restoration project. In their handbook on the subject, Baggett et al. (2014) suggest the following metrics:

(1) reef areal dimension;
(2) reef height;
(3) oyster density;
(4) oyster size-frequency distributions; and
(5) water quality parameters.

Additionally, the following environmental variables should be monitored to aid with interpretation of metrics data:

(1) water temperature;
(2) salinity; and,
(3) dissolved oxygen.

These pre- and post- construction monitoring and assessment objectives should be clearly defined in the restoration plan. Additional metrics may be added to the plan depending on the purpose, for example, assessing fish and invertebrate populations pre- and post-construction. Key metrics for success are identified by project purpose type in Table 5.

For all metrics, Baggett et al. (2014) recommend that sampling be done at the restoration site and at a control or natural reference site in the year prior to construction, and during post-construction monitoring.

For more specific information and guidance on shellfish restoration projects, consult:

Atlantic States Marine Fisheries Commission. 2007. The Importance of Habitat Created by Molluscan Shellfish to Managed Species Along the Atlantic Coast of the United States. Habitat Management Series #8. 108pp.

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock & S. Morlock. 2014. Oyster habitat restoration monitoring and assessment handbook. The Nature Conservancy, Arlington, Virginia. 96pp.

Brumbaugh, R.D., M.W. Beck, L.D. Coen, L. Craig & P. Hicks. 2006. A Practictioners' Guide to the Design and Monitoring of Shellfish Restoration Projects: An Ecosystem Services Approach. The Nature Conservancy, Arlington, Virginia. 30pp.

Leonard, D. & S. Macfarlane. 2011. Best Management Practices for Shellfish Restoration. Prepared for the ISSC Shellfish Restoration Committee, October 2, 2011.

Literature Cited

Anon.1784. An Act for Encouraging and Regulating Fisheries. In: Acts and Laws of the State of Connecticut in America 1784.

Anon.1855. An Act regulating and protecting the planting of oysters. Pp 112-115 in: Public Acts State of Connecticut 1855, Chapter XCII.

Anon. 2015. Long Island Sound Comprehensive Conservation and Management Plan. A Publication of the Long Island Sound Study. 70pp.

Anon. 2016. Connecticut Shellfish Vision Plan: Part 1. A Publication of the Connecticut Sea Grant. 8pp.

Anderson, T. 2004. This Fine Piece of Water: An Environmental History of Long Island Sound. Yale University Press. 274pp.

Auster, P.J., R.J. Malatesta & S.C. LaRosa. 1995. Patterns of microhabitat utilization by mobile megafauna on the southern New England (USA) continental shelf and slope. *Marine Ecology Progress Series*. 127:77-85.

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock & S. Morlock. 2014. Oyster habitat restoration monitoring and assessment handbook. The Nature Conservancy, Arlington, Virginia. 96pp.

Beck, M.W., R.D. Brumbaugh, L. Airoldi, A. Carranza, L.D. Coen, C. Crawford, O. Defeo, G.J. Edgar, B. Hancock, M.C. Kay, H.S. Lenihan, M.W. Luckenbach, C.L. Toropova, G. Zhang & X. Guo. 2011. Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management. *BioScience*. 61(2):107–116.

Bellantoni, N.F. & B. Dorr. 1985. The Mago Point Site. Paper presented at the 51st Annual Meeting of the Archaeological Society of Connecticut, Milford, Connecticut.

Bellantoni, N.F. & C. Harty. 2001. The Eastern oyster, changing uses from an archeological perspective. *Cultural Resource Management*. 24(4):29-30.

Blackford, E.G. 1885a. The Oyster Beds of New York. *Transactions of the American Fisheries Society*, Fourteenth Annual Meeting. 14:85-89.

Blackford, E.G. 1885b. Report of the Commissioner of Fisheries of the State of New York in Charge of the Oyster Investigation. Albany, New York. 70pp.

Bricker, S.B., J. Ferreira, C. Zhu, J. Rose, E. Galimany, G. Wikfors, C. Saurel, R. Landeck Miller, J. Wands, P. Trowbridge, R. Grizzle, K. Wellman, R. Rheault, J. Steinberg, A. Jacob, E. Davenport, S. Ayvazian, M. Chintala & M. Tedesco. 2015. An Ecosystem Services Assessment using bioextraction technologies for removal of nitrogen and other substances in Long Island Sound and the Great Bay/Piscataqua Region Estuaries. NCCOS Coastal Ocean Program

Decision Analysis Series No. 194. National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, MD and United States Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, Narragansett, RI. 154 pp + 3 appendices.

Brousseau, D.J. 1982. Gametogenesis and spawning in a population of *Geukensia demissa* (Pelecypoda: Mytilidae) from Westport, Connecticut. *Veliger*. 24: 247-251.

Brousseau, D.J. 1983. Aspects of reproduction of the blue mussel *Mytilus edulis* (Pelecypoda: Mytilidae) in Long Island Sound. *Fishery Bulletin*. 81(4):733-739.

Buroker, N.E. 1983. Population genetics of the American oyster *Crassostrea virginica* along the Atlantic coast and Gulf of Mexico. *Marine Biology*. 75:99-112.

Bushek, D., D. Richardson, M. Yvonne Bobo & L.D. Coen. 2004. Quarantine of oyster shell cultch reduces the abundance of *Perkinsus marinus*. *Journal of Shellfish Research*. 23(2):369-373.

Carlton, J.T. 2001. Introduced Species in U.S. Coastal Waters: Environmental Impacts and Management Priorities. Pew Oceans Commission, Arlington, Virginia. 32pp.

Coen, L.D., R.D. Brumbaugh, D. Bushek, R. Grizzle, M.W. Luckenbach, M.H. Posey, S.P. Powers & S.G. Tolley. 2007. AS WE SEE IT. Ecosystem Services related to oyster restoration. *Marine Ecology Progress Series.* 341:303-307.

Cohen, A. & C.J. Zabin. 2009. Oyster Shells as Vectors for Exotic Organisms. *Journal of Shellfish Research*. 28:163-167.

Colden, A.M., R.J. Latour & R.N. Lipcius. 2017. Reef height drives threshold dynamics of restored oyster reefs. *Marine Ecology Progress Series*. 582:1-13.

Collins, J.W. 1891. Notes on the oyster fishery of Connecticut. In: Bulletin of the U.S. Fish Commission Volume IX for 1889. Government Printing Office, Washington, D.C.

Dame, R.F., R.G. Zingmark & E. Haskin. 1984. Oyster reefs as processors of estuarine materials. *Journal of Experimental Marine Biology and Ecology*. 83(3):239-247.

De Broca, P. 1876. On the oyster industries of the United States. Pp. 271-320 in: Report to the U.S. Fish Commission, 1873-74 and 1874-75. Washington, D.C., 1876.

Dreyer, G.D. & W.A. Niering. 1995. Bulletin No. 34: Tidal marshes of Long Island Sound: Ecology, History and Restoration. Bulletins. Paper 34. 44pp.

Eastern Oyster Biological Review Team. 2007. Status review of the eastern oyster (*Crassostrea virginica*). Report to the National Marine Fisheries Service, Northeast Regional Office. February 16, 2007. NOAA Tech. Memo. NMFS F/SPO-88, 105p.

Ferreira, J.G., A.J.S. Hawkins & S.B. Bricker. 2011. The Role of Shellfish Farms in Provision of Ecosystem Goods and Services. Pp. 3-31 in: *Shellfish Aquaculture and the Environment*, S.E. Shumway, editor. Blackwell-Wiley.

Galimany, E., J.M. Rose, M.S. Dixon & G.H. Wikfors. 2013. Quantifying feeding behavior of ribbed mussels (*Geukensia demissa*) in two urban sites (Long Island Sound, USA) with different seston characteristics. Estuaries and Coasts. 36(6):1265–1273.

Galpin, V.M. 1989. New Haven's Oyster Industry 1638-1987. The New Haven Historical Society. New Haven, Connecticut. 78 pp.

Galtsoff, P.S. 1930. The fecundity of the oyster. *Science*. 72:97-98.

Galtsoff, P.S. 1964. The American oyster, *Crassostrea virginica* Gmelin. U.S. Fish and Wildlife Service Fishery Bulletin 64. 480 pp.

Gobler, C.J. & S.C. Talmage. 2013. Short and long-term consequences of larval stage exposure to constantly and ephemerally elevated carbon dioxide for marine bivalve populations. *Biogeosciences*. 10:2241–2253.

Grabowski, J. H. & C. H. Peterson. 2007. Restoring oyster reefs to recover ecosystem services. Pp. 281–298 in: *Ecosystem engineers: plants to protists*, Cuddington, K., J. E. Byers, W. G. Wilson & A. Hastings, editors, Elsevier, Burlington, Massachussetts.

Green, M.A., M.E. Jones, C.L. Boudreau, R.L. Moore & B.A. Westman. 2004. Dissolution mortality of juvenile bivalves in coastal marine deposits. *Limnology and Oceanography*. 49(3):727–734.

Hotchkiss, S.M. 1890. Part IV. The Fisheries Industry, The Oyster Industry. In: *Fifth Annual Report of the Bureau of Labor Statistics of the State of Connecticut, for the Year Ending November 30, 1889*. The Case, Lockwood & Brainard Company, Hartford, Connecticut. 215 pp.

Ingersoll, E. 1881. The history and present condition of the fishery industries: The oyster-industry. U.S. Census Bureau. Tenth Census of the United States. Government Printing Office, Washington, D.C.

Juet, Robert. 2006. Juet's Journal of Hudson's 1609 Voyage of the Half Moon, from the 1625 Edition of *Purchas His Pilgrimes* (modified version). Transcribed by Brea Barthel, New Netherland Museum/Half Moon.

Juli, H.D. & G.D. Dreyer. 1992. Bulletin No. 33: Archaeology in the Connecticut College Arboretum. Bulletins. Paper 33.

Kellogg, J.L. 1910. Shell-Fish Industries. H. Holt and Company, New York, New York. 361 pp.

Kennedy, V.S. 1996. Biology of larvae and spat. Pp. 371-422 in: The Eastern Oyster, *Crassostrea virginica.* V.S. Kennedy, R.I.E. Newell & A.F. Eble, editors. Maryland Sea Grant College, University of Maryland, College Park, Maryland. 772 pp.

Kent, F.E.A., J.M. Mair, J. Newton, C. Lindenbaum, J.S. Porter & W.G. Sanderson. 2017. Commercially important species associated with horse mussel (*Modiolus modiolus*) biogenic reefs: A priority habitat for nature conservation and fisheries benefits. *Marine Pollution Bulletin*. 118(1-2):71-78.

La Peyre, M.K, K. Serra, T.A. Joyner, A. Humphries. 2015. Assessing shoreline exposure and oyster habitat suitability maximizes potential success for sustainable shoreline protection using restored oyster reefs. *PeerJ* 3:e1317.

Lightfoot, K.G. 1985. Shell Midden Diversity: A Case Example from Coastal New York. *North American Archaeologist.* 6:289-324.

Lopez, R.A., R. Boehm, M. Pineda, P. Gunther & F. Carstensen. 2017. Economic Impacts of Connecticut's Agricultural Industry: Update 2015. Zwick Center for Food and Resource Policy Outreach Report No. 47, University of Connecticut, September 2017.

Loosanoff, V.L. 1966. Timing and intensity of setting of the oyster *Crassostrea virginica*, in Long Island Sound. *The Biological Bulletin.* 130(2):211-227.

Loosanoff, V.L. 1969. Maturation of gonads of oysters *Crassostrea virginica* of different geographical areas subjective to relatively low temperatures. *Veliger*. 11(3):153-163.

Mackenzie, C. L. Jr. 1996. History of oystering in the United States and Canada, featuring the eight greatest oyster estuaries. *Marine Fisheries Review*. 58:1–78.

Mann, R. 1983. The role of introduced bivalve mollusc species in mariculture. *Journal of the World Mariculture Society*. 14:546-559.

Meyer, D.L., E.C. Townsend & G.W. Thayer. 1997. Stablization and Erosion Control Value of Oyster Cultch for Intertidal Marsh. *Restoration Ecology*. 5(1):93-99.

Naylor, R. L., S. L. Williams & D. R. Strong. 2001. Aquaculture: a gateway for exotic species. *Science.* 294:1655-1656.

Newell, R.I.E., T.J., Hilbish, R.K. Koehn & C.J. Newell. 1982. Temporal variation in the reproductive cycle of *Mytilus edulus* (Bivalvia, Mytilidae) from localities on the east coast of the United States. *Biological Bulletin*. 162:299-310.

Newell, R.I.E. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North and Mid-Atlantic)—blue mussel. U.S. Fish and Wildlife Service Biological Report. 82(11.102). U.S. Army Corps of Engineers, TR E1-82-4. 25pp.

New York State Department of Environmental Conservation. 2005. New York State Comprehensive Wildlife Conservation Strategy. http://www.dec.ny.gov/index.html. Accessed 13 March 2018.

Pike, R.G., W.M. Hudson & G.N. Woodruff. 1882. The First Report of the Shell Fish Commissioners of the State of Connecticut to the General Assembly, January Session 1882. Pp37-132 in: The Sixteenth Annual Report of the Fish Commissioners. The Case, Lockwood & Brainard Company, Hartford, Connecticut.

Pomeroy, R.D., D. Yang & T. Getchis. 2017. Catching Value: An Economic Assessment of Connecticut's Recreational Shellfish Sector. Connecticut Sea Grant. Working Paper.

Praus, A. 1942. Examination at the Old Lyme Shell Heap. *Bulletin Archaeological Society of Connecticut*. 13:3-66.

Riisgård, H.U. 2001. On measurement of filtration rates in bivalves-the stony road to reliable data: review and interpretation. *Marine Ecology Progress Series*. 211:275-291.

Rowe, H.C. 1919. The Great Decline of the Oyster Industry in Connecticut and Rhode Island. Reprinted in 2011 in: *Transactions of the American Fisheries Society*. 49(1): 33-37.

Ruesink, J.L, H.S. Lenihan, A.C. Trimble, K.W. Heiman, F. Micheli, J.E. Byers & M.C. Kay. 2005. Introduction of Non-Native Oysters: Ecosystem Effects and Restoration Implications *Annual Review of Ecology, Evolution, and Systematics*. 36:643-689.

Scyphers, S.B., S.P. Powers, K.L. Heck, Jr. & D. Byron. 2011. Oyster Reefs as Natural Breakwaters Mitigate Shoreline Loss and Facilitate Fisheries. *PLoS One*. 6(8):1-12

Shumway, S.E. 1996. Natural environmental factors. Pp. 467-513 in: The Eastern Oyster *Crassostrea virginica*, V.S. Kennedy, R.I.E. Newell & A.F. Eble, editors. Maryland Sea Grant College, University of Maryland, College Park, Maryland. 772 pp.

Stewart, L.L. 1972. The seasonal movements, population dynamics, and ecology of the lobster (*Homarus americanus*) in Long Island Sound. Doctoral dissertation. University of Connecticut, Storrs, Connecticut. 112 pp.

Sunila, I., L. Williams, S. Russo & T.L. Getchis. 2004. Reproduction and pathology of blue mussels, *Mytilus edulis* (L.) in an experimental longline in Long Island Sound, Connecticut. *Journal of Shellfish Research.* 23:731-740.

Sweet, G. 1941. Oyster Conservation in Connecticut: Past and Present. *Geographical Review*. 31(4):591-608.

Trapp, J.E. & R.B. Brockett. 1999. Oystering in Milford, A Brief History. C.J. Caroll (Editor). Sponsored by Briarpatch Enterprises, Inc., Milford, Connecticut.

Visel, T.C. 2014. New Haven's Lost Natural Oyster Beds. Revised for Capstone, January 2014. Sound School Adult Education and Outreach Program. The Sound School Regional Aquaculture Center, New Haven, Connecticut.

Wells, H.W. 1961. The fauna of oyster beds, with special reference to the salinity factor. Ecological Monographs. 31:266-329.

Waldbusser, G.G., H. Bergschneider & M.A. Green. 2010. Size-dependent pH effect on calcification in post-larval hard clam *Mercenaria* spp. *Marine Ecology Progress Series.* 417: 171-182.

Waldbusser, G.G., B. Hales, C.J. Langdon, B.A. Haley, P. Schrader, E.L. Brunner, M.W. Gray, C.A. Miller, I. Gimenez & G. Hutchinson. 2015. Ocean Acidification Has Multiple Modes of Action on Bivalve Larvae. *PLoS One*. 10(6):1-29.

Winslow, F. 1881. Deterioration of American Oyster Beds II. *Popular Science Monthly*. 20(2):145-155.

zu Ermgassen, P.S.E., M.D. Spalding, B. Blake, L.D. Coen, B. Dumbauld, S. Geiger, J.H. Grabowski, R. Grizzle, M. Luckenbach, K. McGraw, B. Rodney, J.L. Ruesink, S.P. Powers & R. Brumbaugh. 2012. Historical ecology with real numbers: Past and present extent and biomass of an imperiled estuarine habitat. Proceedings of the Royal Society B rspb.royalsocietypublishing.org Published on 12 June 2012.

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List of Tables

Table 1. List of federally-managed species present in the Long Island Sound and associated with natural shellfish beds
After Atlantic States Marine Fisheries Commission 2007

Common Name (Latin Name)
American eel (*Anguilla rostrata*)
American lobster (*Homarus americanus*)
Atlantic herring (*Clupea harengus*)
Atlantic menhaden (*Brevoortia tyrannus*)
Atlantic sturgeon (*Acipenser oxyrinchus*)
Black sea bass (*Centropristis striata*)
Bluefish (*Pomatomus saltatrix*)
Horseshoe crab (*Limulus polyphemus*)
Scup (*Stenotomus chrysops*)
Shad and river herring (*Alosa* spp.)
Spiny dogfish (*Squalus acanthias*)
Spot (*Leiostomus xanthurus*)
Spotted seatrout (*Cynoscion nebulosus*)
Striped bass (*Morone saxatilis*)
Summer flounder (*Paralichthys dentatus*)
Tautog (*Tautoga onitis*)
Weakfish (*Cyanoscion regalis*)
Winter flounder (*Pleuronectes americanus*)

Table 2. Designated natural oyster beds in Connecticut

Location	Town (acres)	State (acres)	Notes
Greenwich	1,620	872	
Stamford	500	0	
Darien (Noroton)	300	307	
Norwalk	1,700	see notes	combined with Darien; prior accounts indicate 160 acres (Collins 1891)
Westport	1,300	see notes	combined with Fairfield; prior accounts indicate 90 acres (Collins 1891)
Fairfield	800	1,237	
Bridgeport	1,240.8	334	
Stratford	1,442.5	3,055	
Milford	1,200	0	
New Haven (Orange)	2,900	0	
Branford	80.5	0	
Madison/Guilford	*	0	200 acres; East River, Guilford River (Collins 1891, Ingersoll 1881)
Clinton	420	0	
Westbrook	*	0	50 acres (Collins 1891)
Old Saybrook	*	0	150 acres, Oyster River (Collins 1891, Ingersoll 1881)
East Lyme/Waterford	*	0	5 acres; Niantic River (Collins 1891, Ingersoll 1881)
New London/Waterford	*	0	20 acres; Thames River, Alewife Cove (Collins 1891, Ingersoll 1881)
Groton	*	0	25 acres; Poquonnock River (Collins 1891)
Stonington	*	0	Mystic River (Bogart 1889)
Total	**13,503.8**	**5,805**	

*Stamford, Milford, New Haven, East Haven, and the towns east of Branford (with the exception of Clinton), did not avail themselves of section 2326, General Statutes, 1888, and therefore their natural beds were not identified in statute.

Table 3. New York historic natural oyster beds. *After Blackford (1885b)*

Location	Area (Acres)
College Point	64
Whitestone Point (East)	27
Hamelin Flats (East)	31
Throggs Neck Bed (South)	13
Hamelin Flats (West)	170
Gangway Buoy	79
Barker's Point Bed	149
Execution Rock Bed	139
Hempstead Harbor	8,110
Peacock Point	907
Bed No. 11	31
Bed No. 12 (near fox Island)	26
Lloyd's Neck Bed	101
Princess Bay (Swash Bed, New York Bay, Hoffman Island, Great Beds Light)	651
Eaton's Point Bed	278
Stony Brook Bed	143
Nissequogue Bed	303
Owl's Head	101
Gravesend Bay	875
Whitestone Point Bed (West)	10
Willett's Point	208
Little Neck Bay	1,481
Throggs Neck (North)	28
Great Neck and Saddle Rock	639
Hart Island Bed	71
City Island Bed	331
Pelham Bay	108
Sands Point Bed	36
Arthur Kill (Staten Island Sound)	476
Total	**15,586**

Note: Town shellfish beds were not surveyed but estimated to comprise at least 20,000 acres. Some beds are located just outside of the Long Island Sound proper.

Table 4. Long Island Sound shellfish beds by type and size

	Connecticut		New York	
Bed Type	**Area, historic (acres)**	**Area, present day (acres)**	**Area, historic (acres)**	**Area, present day (acres)**
Natural	5,805[1]	5,327[4]	15,586	unknown
Commercial	70,133[2*]	50,002[5**]		unknown
Recreational	unknown	0	unknown	unknown
State Waters	**335,000[2**]**	**323,130**		
Natural	13,503[3]	16,589[5]	20,000	unknown
Commercial	6,875[2]	30,077[5***]		unknown
Recreational	unknown	17,766[5]	unknown	unknown
Town Waters	**35,000[2**]**	**65,611**		
Total	**370,000[2**]**	**388,741**		

[1] Section 2328 of the Connecticut General Statutes, Revision of 1888
[2] Collins 1891
[3] Section 2326 of the Connecticut General Statutes, Revision of 1888
[4] Section 3295 of the Connecticut General Statutes (CGS), revision of 1918
[5] Connecticut Department of Agriculture, Bureau of Aquaculture 2018
*This area includes perpetual franchises and state shellfish lease areas (leasing began in 1915).
**This figure is representative of the total area minus ledges and islands which comprise approximately 15,000 acres (Collins 1891). Slight differences in historic versus current acreages reflect improved accuracy through the use of GIS.
***This area includes grants from the King and Crown of England, deeded shellfish beds, and town shellfish lease/license/co-management areas.

Table 5. Key restoration project metrics by project purpose

Project Purpose	**Metric**	**Recommendation**
Construction of any non-harvested reefs for any purpose	reef height has recently been determined to be a key predictor of restoration success or failure. Low-relief reefs can be impacted by sediment accumulation that smothers adult oysters and reduces the available surface area to recruit larval oysters.	Colden et al. (2017) suggest that restored reefs should extend at least 0.3 meters above the bottom, and that harvest should be prohibited unless the reefs remain above the reef-height threshold.
Improving water clarity	light penetration	
Improving water quality	nutrient sequestration, other water quality parameters	
Improving fish and wildlife habitat;	density of selected species (fish, invertebrates, birds) and/or faunal groups.	
Improving shoreline stabilization and erosion control	shoreline loss/gain (change in shoreline position); shoreline profile/elevation change; and, density and percent cover of marsh/mangrove plants; submerged aquatic vegetation coverage which may occur with water clarify improvements; wave energy and tidal flows measured seaward and landward of the restored reef	
Improving capture fisheries	shellfish landings data	

List of Figures

Figure 1. Intertidal oyster bed (*John Short*)

Figure 2. The life cycle of the eastern oyster *Crassostrea virginica.* (*Connecticut Sea Grant*)

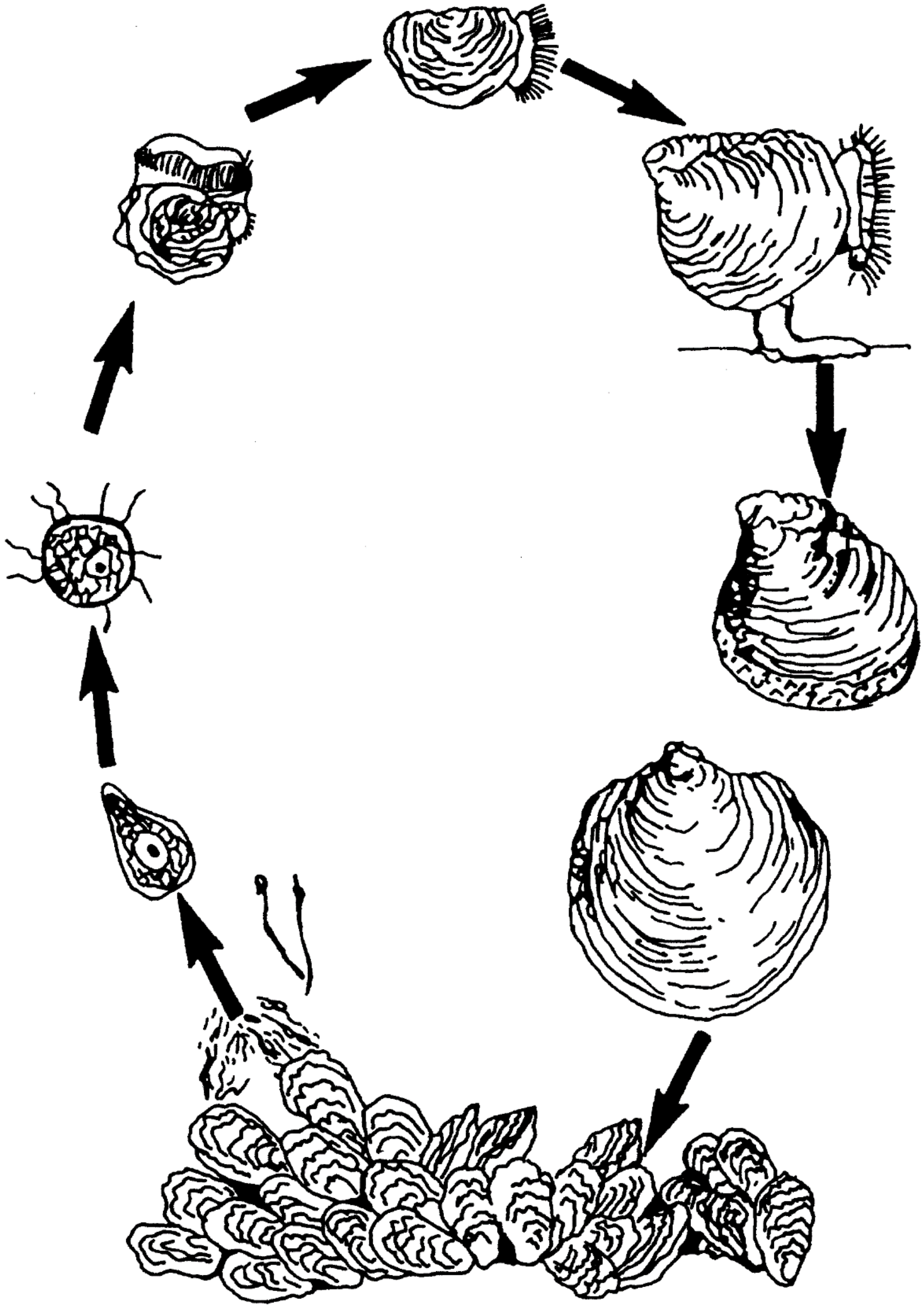

Figure 3. Ribbed mussels *Geukensia demissa* in a salt marsh. (*Tessa Getchis*)

Figure 4a. Historic oyster grounds, Connecticut - Western Long Island Sound
(James P. Bogart, Part of the Fifth Annual Report of the Bureau of Labor Statistics, 1889)

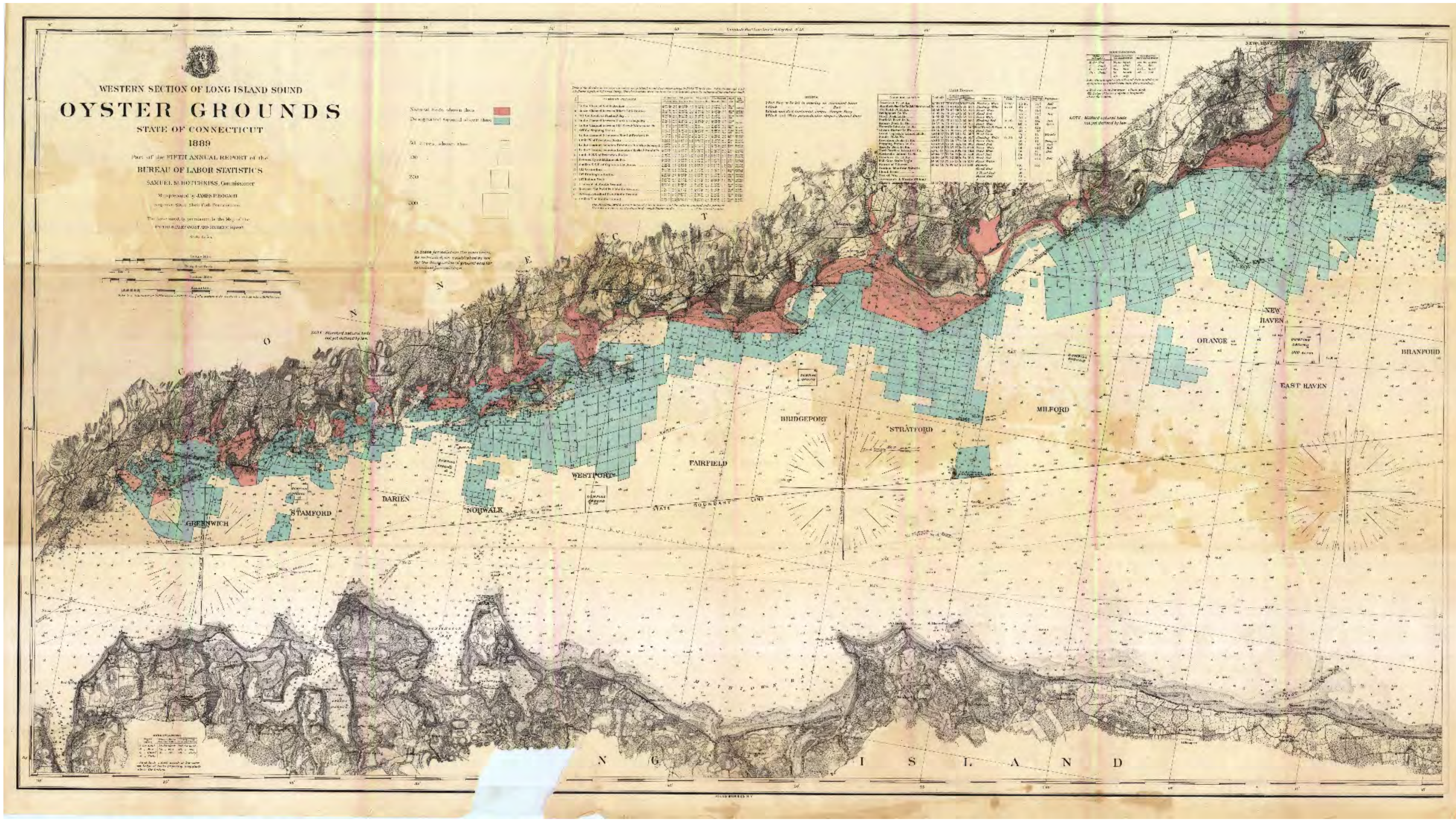

Figure 4b. Historic oyster grounds, Connecticut - Eastern Long Island Sound
(James P. Bogart, Part of the Fifth Annual Report of the Bureau of Labor Statistics, 1889)

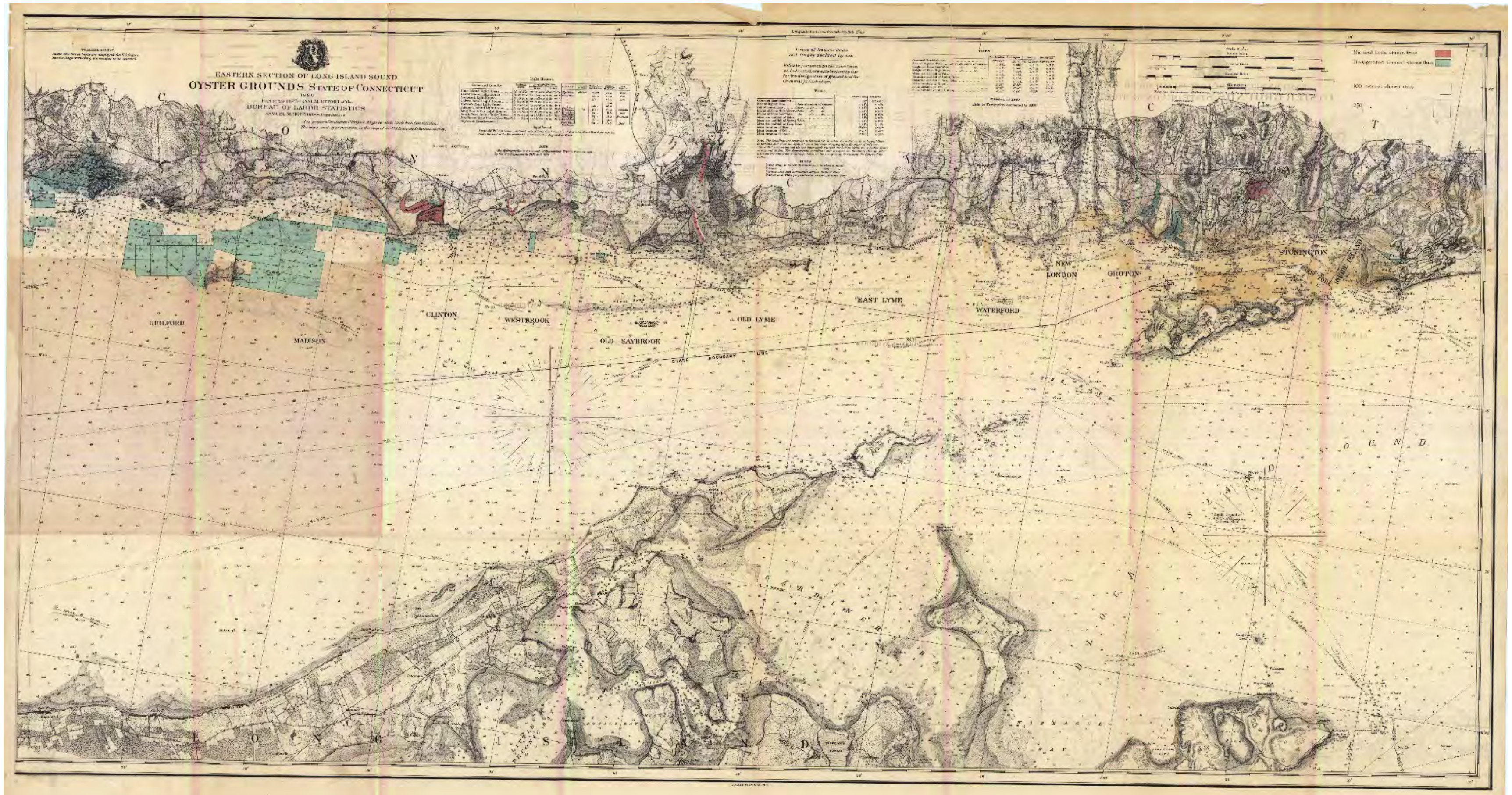

Figure 5a. Current shellfish grounds, Connecticut - Western Long Island Sound
(Michael Zuber, Connecticut Department of Agriculture, Bureau of Aquaculture, 2018)

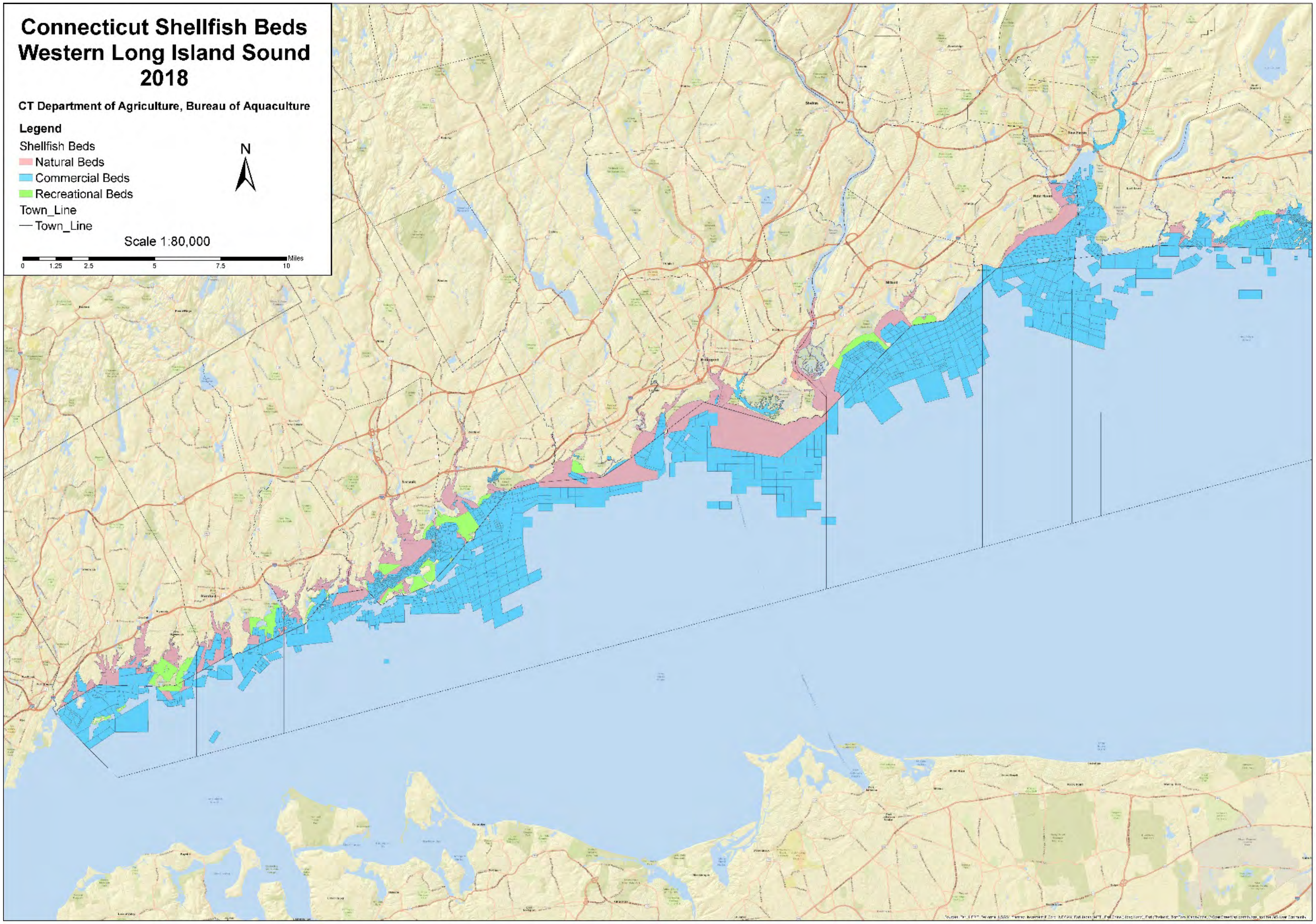

Figure 5b. Current shellfish grounds, Connecticut - Eastern Long Island Sound
(Michael Zuber, Connecticut Department of Agriculture, Bureau of Aquaculture, 2018)

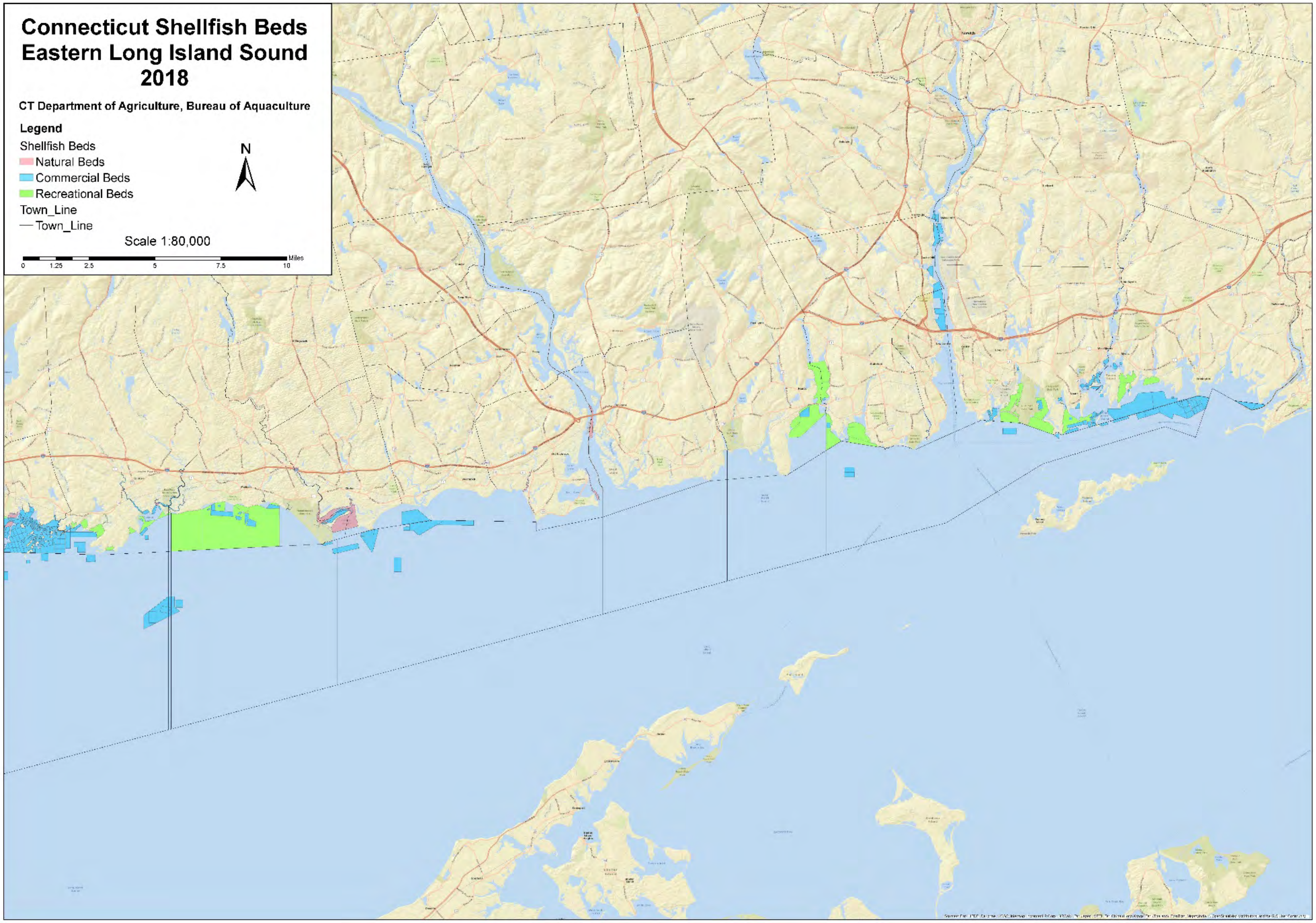

Figure 6. Long Island Sound Boundary and Shellfish Jurisdiction Lines
(Michael Zuber, Connecticut Department of Agriculture, Bureau of Aquaculture, 2018)