Status and Trends of Hard Clam, *Mercenaria mercenaria*, Shellfish Populations in Barnegat Bay, New Jersey

Prepared for the Barnegat Bay Partnership

by

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Dedicated to Mel Carriker, who was an inspiration to all of us who knew him for his exhaustive knowledge about larval ecology and molluscs in general, but especially for his generosity and friendship. His work about hard clam larvae in Little Egg Harbor, NJ, reported here, remains a classic and unsurpassed piece of work on the subject.

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Appendix I. Lease area survey data from NJDEP, Division of Shellfisheries for Barnegat and Little Egg Harbor. SL = Sublegal, LN = Littleneck, CS = Cherrystone and CH = chowder (see Fig. 46 A through E for lease locations). Size ranges for each commercial size class given in the text. Data shown represent all lease survey data available.

Appendix II. Shorefront area survey data from NJDEP, Division of Shellfisheries for Barnegat and Little Egg Harbor Bays. SL = Sublegal, LN = Littleneck, CS = Cherrystone and CH = Chowder. Size ranges for each given in the text. Based on all available survey data.

1. **Introduction: goals of the report**

The northern quahog (= hard clam), *Mercenaria mercenaria* (Linnaeus, 1758), is the dominant suspension-feeding shellfish (bivalve) resource occurring in high salinity, coastal bay (lagoonal) ecosystems on the US Atlantic coast. It supports important commercial and recreational fisheries, and is also the most valuable aquaculture species on the US east coast [valued at $60 M in 2002 (USDA 2006)]. Because of its wide distribution in Atlantic estuaries in relation to temperature, sediment type and other environmental conditions, and its long lifespan (several decades), the hard clam can serve as a primary indicator of the overall health of the Barnegat Bay-Little Egg Harbor (BB-LEH) estuary. Two epifaunal (non-burrowing) shellfish species, the oyster, *Crassostrea virginica* and the northern bay scallop, *Argopecten irradians irradians*, were also once an important resource in this estuary, but are not the focus of this report.

The main goal of this paper is to review the historical and current status of hard clam populations in BB-LEH and evaluate their potential for rehabilitation under present environmental conditions. We use prior stock assessments conducted by the State of New Jersey (NJ), and published studies to construct a history of the hard clam in this estuary. These data provide a direct assessment of the past levels of abundance of *M. mercenaria* in the estuary in relation to environmental conditions. They can assist in identifying suitable locations and strategies for restoration, as well as identify gaps of information or mitigation measures required to ensure that the estuary can sustain clam populations. In addition, size-frequency distributions, and size-at-age information added to the population survey information can help elucidate long-term trends in the populations of this resource.

The first part of the report focuses on characterizing the principal physico-chemical and biological environmental conditions in the BB-LEH ecosystem based on both historical and more recently collected data where available, that can point to temporal, decadal changes occurring in this estuary. It emphasizes their relevance to hard clam, *M. mercenaria*, populations based on environmental tolerance limits and optimum conditions for growth, reproduction and survival of various life history stages. The second portion documents what is known about the status of *M. mercenaria* populations in this estuary. Where relevant, comparisons are made with the status of hard clam populations in relation to environmental conditions, as well as stock enhancement efforts, in mid-Atlantic coastal lagoonal ecosystems, primarily the south shore Long Island, NY, estuaries. The latter have been the subject of more comprehensive, detailed studies and therefore provide useful information for future management of the hard clam resource in the BB-LEH estuary. Key conclusions are listed at the end of each section and final conclusions and recommendations for future research are highlighted at the end of the report.

2.a. The Barnegat Bay-Little Egg Harbor ecosystem: the physico-chemical environment

The BB-LEH Estuary, a coastal lagoonal ecosystem, is located in the mid-Atlantic USA, in Ocean County, central NJ, between 39º31’N and 40º06’N latitude and 74º02’W and 74º20’W longitude (Fig. 1). . Coastal lagoons are typically well mixed vertically by wave and current action. Because of their shallow depth, water column stratification is usually weak or absent.

Tidal range generally averages <1 m, ranging from ~60 cm in the inlets to 15-20 cm at points furthest away from the inlets (Psuty 2004). Since the photic zone usually extends to the lagoonal floor, benthic production [e.g. by seagrasses (SAV), macroalgae, and epiphytic microalgae] comprises a significant fraction of the total primary production of the system. In addition, there is strong benthic-pelagic coupling due to high metabolic rates of the benthic primary producers that mediate nutrient cycling processes (McGlathery et al. 2007). Strong coupling between coastal lagoons, their watersheds and the atmosphere, with limited buffering due to protracted water residence times may thus result in low resilience to stressors. Agricultural activity, urbanization, and nonpoint source pollution are drivers or stressors of environmental change in many coastal lagoons, particularly in the mid-Atlantic region. Where watershed population growth and development are high, anthropogenic activities often compromise the structure, function, and integrity of these productive systems. Other mid-Atlantic coastal lagoons that have experienced increasing human development and nutrient enrichment include the South Shore Estuaries (SSE), Long Island (LI), NY, including Great South Bay, NJ Inland Coastal Bays, Delaware Inland Bays (Rehoboth, Indian, and Little Assawoman bays), northern MD coastal bays (Assawoman Bay, Isle of Wight Bay, and St. Martin River), and southern MD coastal bays (Newport, Sinepuxent, and Chincoteague bays (Fig. 2). Table 1 lists geomorphological and physico-chemical characteristics of these coastal lagoons. Mid-Atlantic coastal lagoons have received nationwide classification as highly susceptible to eutrophication (Bricker et al. 1999, 2007). The BB-LEH Estuary was designated in 1995 by the US Environmental Protection Agency (EPA) as a National Estuary Program (NEP) site, and Little Egg Harbor lies within the boundaries of the Jacques Cousteau National Estuarine Research Reserve. Maryland Coastal Bays also won designation as part of the NEP in the 1990s.

The BB-LEH Estuary is ~70 km long, 2-6.5 km wide, with a surface area of 280 Km^2 and volume of 3.54×10^8 m^3 (Kennish, 2001); depths range from 1.3 m in the northern half of the system to ≥2.0 m in LEH, such that 73% of the bay is <2 m deep at mean low water (Mahoney et al. 2006). Water temperature ranges from -1.5 to 30ºC, and salinity from ~10 to 32. The physiographic features of the bay and barrier island complex (Island Beach and Long Beach Island, N and S of Barnegat Inlet respectively), result in limited flushing and protracted bay water residence with a strong seasonal component, ranging from a low of 24 days in winter, up to a maximum of 74 d in summer, and an annual average of 49 d (Guo et al. 2004). Exchange with ocean water occurs through Point Pleasant Canal, a dredged channel on the north which contributes a minor amount of discharge, and primarily two natural inlets, Barnegat Bay Inlet in central BB, and Little Egg Inlet in the south, which connects with the Great Bay-Mullica River Estuary (Fig. 1). Freshwater input occurs primarily along the western side of the bay, via the Toms River in the north and freshwater creeks, storm drains and groundwater seepage (Mahoney et al. 2006). Groundwater influx provides the bulk (> 80%) of the freshwater discharge.

The surrounding watershed (watershed:estuary areal ratio is 6.5:1, Table 1) now has ~575,000 year-round residents, although more than 1.2 million people inhabit the watershed during the summer tourist season (Kennish and Fertig 2012). The watershed has experienced rapid urban development over past decades, especially in the northern reaches of Barnegat Bay, as illustrated by the changes in land use between 1972 and 2010 (Fig. 3). Thus, the total area of land developed has increased linearly between 1985 and 2006. Urbanization has largely occurred at the expense of upland forest and has increased at a faster rate than the growth rate of the population, leading to so-called "urban sprawl" (Hasse and Lathrop 2010). This rapid human development of the shoreline and the watershed is associated with environmental consequences, including increased nutrient loading, and creation of an increasing percentage of impervious surface. The latter in turn increases the amount of surface runoff. Bulkheading decreases connectivity with the uplands and eliminates areas that could become marsh as sea level rises. All these factors lead to deterioration of environmental conditions in the estuary.

Human activity may also impact hard clam populations via physical disturbance, caused by dock construction, dredging and boat scarring. Bottom dredging for boat access as well as for sediment mining following major storms, has affected 790 ha of the BB-LEH estuary (Lathrop and Haag 2011), and will cause localized, short-term increases in turbidity. Longer term changes in bottom topography may alter flow patterns. In particular, southern BB, south of Barnegat Inlet, has been extensively dredged along the eastern shore. Barnegat Inlet has also undergone major changes due to shifting sand bars, dredging for channel navigation and modifications to stabilize the inlet. These have affected the Sedge Is. Marine Conservation Zone (MCZ) and also resulted in loss of extensive eelgrass beds (Lathrop and Haag 2011).

Boat traffic could also affect hard clam populations. One obvious impact could be via disruption by the sediments by propeller wash, which would expose clams and make them more vulnerable to predators. Less obvious damage could result from the large quantities of water that go through the propeller and engine cooling system. Boating is a significant activity in the BB-LEH system and it peaks at the same time as the clam larvae are in the water. The shear forces exerted by the propeller are enough to potentially damage the larvae. In addition, two cycle outboards discharge their exhaust directly into the system, and this discharge includes various hydrocarbon compounds (Albers, P.H. 2002), and some of these may compromise larval or postlarval survival.

Given that this report also includes some data on clam populations in the Mullica River-Great Bay (MR-GB) estuary, it is relevant to describe salient characteristics of this system for comparison with BB-LEH. The MR-GB estuary is bordered by extensive salt marshes and very limited development along its watershed which lies within the boundaries of the Jacques Cousteau National Estuarine Research Reserve (JCNERR). It is thus a relatively pristine system with very limited anthropogenic impacts (Kennish and O'Donnell 2002). It has a mean depth of < 2 m at mean low water, is well oxygenated, and exhibits a strong salinity gradient ranging from ~ 15 at Chestnut Neck, ~ 13 km upstream of the Mullica River mouth, to ~ 30 near the mouth of Little Egg Inlet. Great Bay, with an area of 41.6 km^2, is characterized by a counterclockwise circulation gyre, with water entering through the inlet flowing along the northern part of the bay, reflected in the higher salinities here than in the southern portions of the bay (Durand 1988).

2.b. Environmental conditions in the BB-LEH in relation to *M. mercenaria* tolerance and optimum ranges: water temperature, salinity, nutrients dissolved oxygen, pH, flow

The northern quahog, *M. mercenaria* is an estuarine species that can occur from the intertidal zone to depths of up to ~ 18 m. It is a eurythermal species requiring bottom salinities > 12 for survival. There is a synergistic effect between salinity and temperature on fitness, i.e. growth and survival of early life history stages. A detailed review of the effect of single and multiple environmental variables on the physiology, including growth rate of *M. mercenaria* was provided by Grizzle et al. (2001) and environmental requirements have also been reviewed by Roegner and Mann (1991) and Pratt et al. (1992). Thus only a brief summary is provided below, to allow comparison with environmental conditions occurring in the BB-LEH estuary.

2.b.i. Temperature

Typical annual seasonal cycles of water temperature in BB-LEH and Great Bay are shown in Figure 4. Winter temperature conditions and the rate of temperature reduction in the fall and temperature rise in the spring are important factors influencing the survival of small hard clam seed (<20 mm shell length, SL) overwintered in the field by local hatcheries (see sec. 9.c.). Prior studies show that when juvenile hard clams are exposed to mild winters, or experience simulated laboratory overwintering at constant temperatures that lie just above the threshold for the onset of the clams' feeding activity (~ 5-6^{o}C), they show significantly higher mortalities than when exposed to lower temperatures at which feeding is totally suppressed (Bricelj et al. 2007, Zarnoch and Schreibman 2008). Subsurface water temperatures from late October to late April are shown for two consecutive years at a site in eastern Beach Haven, Little Egg Harbor (Fig. 5). Winter temperature conditions in 2010/2011 are more typical for this estuary, whereas 2011/2012 reflect milder winter conditions, as temperatures remained $\geq$ 1^{o}C and showed a more gradual decline during the fall. The latter might be more representative of future climate change predictions in the region, which project an average global warming of ~2 to 5^{o}C by 2070-2099, i.e. an increase of ~0.3 to 0.7^{o}C per decade, depending on the model used for these calculations and the level of fossil fuel emissions (Najjar et al. 2010).

The temperature tolerance range of adult hard clams (~1 to 34^{o}C) is much wider than that of larvae (~17 to 30^{o}C) (Fig. 6). Newly fertilized oocytes fail to develop normally in the laboratory at temperatures $\leq$ 15^{o}C (Carriker 1961), and embryos and trochophores experience time-dependent mortalities above 30^{o}C (Kennedy et al. 1974). Growth of larvae ceases at <12.5^{o}C (Davis and Calabrese 1964) (Table 2). Larval settlement (at a SL of 175 to 236 µm) starts within 7 to 24 d depending on temperature (18 to 30^{o}C). The optimum temperature for larval and juvenile growth at salinities ranging from 21.5 to 30, is 22.5-26.6^{o}C; that of juvenile and adult *M. mercenaria* is 20 to 25^{o}C, and declines at lower and higher temperatures (reviewed by Grizzle et al. 2001). Growth ceases entirely below ~6^{o}C when clams stop feeding. Activity of adults is curtailed above 34^{o}C and is optimal between 21 and 31^{o}C (reviewed by Roegner and Mann 1991).

<u>Conclusions</u>:

- Temperature has a strong effect on hard clam populations; it controls spawning, growth and metabolic processes of hard clams. The ranges normally encountered within the BB-LEH lagoon are well within tolarance ranges and will remain so even under predicted global warming scenarios. Increased winter temperatures, however, could have deleterious effects on survival of juvenile hard clams.

2.b.ii. Salinity

Strong spatial gradients in salinity are characteristic of the BB-LEH estuary (Kennish and Fertig, 2011) but these also vary markedly between seasons, as illustrated for April, August and

September in Figure 7 (averaged over 18 years, from 1989 to 2007). A generally north-to-south increase in salinity is evident in the estuary owing to oceanic input at Barnegat Inlet and Little Egg Inlet. Mean salinities are typically lower in Barnegat Bay than in LEH, and are typically lowest north of Berkeley Township (Fig. 7). Typical annual seasonal cycles of salinites in BB-LEH and Great Bay for southern, central and northern sectors of the area surveyed in two consecutive years are shown in Figure 8. These illustrate the range of interannual variability, with salinities generally higher throughout the system in 1999 than in 1998.

Salinity is a major factor determining the distribution of key stenohaline species in the BB-LEH food web, including polyps of the sea nettle, *Chrysaora quinquecirra* (see sec. 8), and *M. mercenaria*. Generally, because of the strong horizontal gradients in the system, salinity is more important than temperature in controlling the distribution of hard clams in BB-LEH. As expected, based on both laboratory experiments and natural distributions, and as observed with temperature, the salinity tolerance range of adult *M. mercenaria* (~12 to 35) is much wider than that of larvae (~20 to 32.5) (Fig. 6), but adults do not grow at ≤ 12 salinity and are intolerant of protracted salinities < 15. The effects and interaction between temperature and salinity on hard clam larval development are illustrated in Table 2. The optimum temperature range for normal development of fertilized eggs and for larval survival is typically reduced with decreasing salinities. Laboratory studies also showed that hard clam veliger larvae did not move vertically across a salinity gradient when they encountered a 15 halocline (Turner & George 1955, cited in Davis 1958). Salinities >32 are detrimental to eggs and larvae, and eggs die at salinities <20 (Davis and Calabrese 1964). Levels <17 impeded larval metamorphosis (reviewed by Funderburk et al. 1991). Salinities between 15 and 17.5 caused a significant reduction in growth of clam larvae (Davis 1958). The optimum salinity for *M. mercenaria* larvae is 26-27. Growth of adults is reduced at salinities <17.5 (Castagna and Chanley 1973), and reproduction is inhibited at <15 salinity. Hard clams are typically only abundant in coastal waters ranging in salinity from 20 to 30. Based on a comparison of summer salinities determined in 1993 and historical values determined by Carriker (1996), Kraeuter et al. (1996) suggested that a reduction in salinities due to the obstruction of incoming oceanic flow through the inlet, or changes in freshwater input to the bay, may have contributed to the decline of hard clam populations in LEH.

Predictions of a climate-driven increase in the intensity of spring precipitation at this latitude (Najjar et al. 2010) and associated changes in salinity may also affect hard clams indirectly via their effect on phytoplankton species composition and the abundance and distribution of euryhaline macrofauna in Atlantic coastal lagoons. Because the Quahog Parasite Unknown (QPX) protistan parasite (see sec. 7) has not been found south of Virginia it is also possible that climate warming would reduce the potential for the QPX parasite to induce mortality in clam populations.

Conclusions:

- Salinity currently is a major factor controlling the distribution of hard clams in the BB-LEH system. This control is exerted through the development process and by limiting the growth and survival of adults at the lower end of the salinity spectrum. This factor should be carefully considered when attempting to identify sites appropriate for clam restoration.

2.b.iii. Dissolved oxygen (DO)

The BB-LEH is shallow and relatively well mixed and thus typically saturated with oxygen. Low DO levels (< 4 mg L^{-1}) have been recorded in the northern segment of the BB-LEH estuary where nutrient concentrations are highest (Kennish et al. 2010). Low DO levels are generally not expected to be limiting for hard clams in BB-LEH, as these generally occur in upper Bay areas of low salinity which are outside the salinity tolerance range of *M. mercenaria* and the species is relatively tolerant of low DO levels (see below). Along transects conducted between 2004-2006 in areas with SAV cover, DO levels in water collected 10 cm above-bottom were relatively high, ranging from 6.78 to 10.49 mg L^{-1}, and pH levels ranged from 7.63 to 8.17 (Kennish et al. 2010). The BB-LEH does not exhibit episodic anoxic/hypoxic outbreaks. There are localized areas where periodic low DO conditions occur such as near the end of Green Street in Tuckerton. Early morning measurements at a commercial shellfish hatchery at this site found DO levels of ~3 mg l^{-1} in the summers of 2005/2006, presumably due to outflow from Tuckerton Creek.

Dissolved oxygen is typically not a limiting factor for hard clams in mid-Atlantic estuaries. The minimum DO level for normal larval development is ~0.5 mg L^{-1}, although growth rates are markedly reduced below 4.2 mg L^{-1} (Morrison 1971). Short-term low DO stress, however, does not affect subsequent development. Laboratory studies showed that pumping rates of *M. mercenaria* decrease linearly with decreasing DO levels from <1 to 5 mg DO L^{-1}, and are significantly reduced relative to controls held at 100% saturation (=5 mg l^{-1}) below 4 mg l^{-1} (Hamwi 1969). Hard clams, however, are relatively tolerant of low DO relative to other bivalves, as they are able to reburrow under very low DO levels (0.9 mg l^{-1}; 16-19^{o}C) (reviewed by Malouf and Bricelj 1989). They can maintain aerobic metabolic rates (VO_2) down to levels of 5.0 mg DO L^{-1}, below which VO_2 declines and anaerobic metabolism contributes an increasing proportion of total metabolism.

Conclusions:

- Except for possibly in very limited localized situations, DO is not a factor that currently limits the distribution of hard clams in the BB-LEH system.

2.b.iv. pH

Hard clams have been described as relatively tolerant of a wide range of pH. Embryos developed at pH values of 7.00-8.75, and larvae survived and grew in a pH range of 6.25 to 8.50. The optimal pH for hard clam larval development was 7.50 to 8.50 (Roegner and Mann 1991). Larval *M. mercenaria* are less tolerant of low pH, however, than oyster, *C. virginica* larvae (Davis and Calabrese 1964).

Recent data indicate, however, that bivalve larvae, which have shells partly composed of aragonite, may be vulnerable to predicted elevated future levels of atmospheric carbon dioxide (CO_2) and concomitant acidification resulting from fossil fuel combustion. Elevated CO_2 levels are associated with a reduction in carbonate ion (CO_3^{-2}) concentrations, pH and calcium carbonate ($CaCO_3$, aragonite and calcite) saturation state in ocean waters. Laboratory experiments have shown that hard clam larvae exposed during development to preindustrial CO_2 levels (~250 ppm, at experimental pH = 8.171) exhibited higher rates of metamorphosis, growth and survival than those at current levels (~400 ppm, pH = 8.052) and those projected to occur by

2100 (~740 ppm, pH = 7.801) (Talmage and Gobler 2010). Ocean acidification driven by upwelling events has been associated with deleterious effects on oyster, *Crassostrea gigas*, larvae in west coast hatcheries (Barton et al. 2012). It is important to note, however, that estuaries often experience pronounced daily fluctuations in pH associated with phytoplankton respiration/photosynthesis cycles. Furthermore, in estuaries acidification also occurs due to the input of rivers (Salisbury et al. 2008), and could affect larvae indirectly via the effects of reduced pH on the bioavailability of toxic metals.

Conclusions:

- Water column pH does not presently appear to be limiting for hard clams in the BB-LEH system (however, see sec. 4.a. for discussion of sedimentary pH and its potential detrimental effects). However, long-term trends in water column pH at appropriate time scales are worthy of future investigation as they could pose a potential threat to bivalve larve.

2.b.v. Water flow

Flow conditions in a shallow estuary such as BB-LEH are strongly influenced by tidal and wind-driven water movement. Water flow is critical for the delivery of the suspended food supply for hard clams living on the bottom. Water flow also affects the transport and distribution of clam larvae in the water column and that of competent pre-metamorphic larvae at the time of settlement. Field experiments have shown that current speed near-bottom (16 cm off-bottom) and hard clam growth followed a parabolic function (Grizzle and Lutz 1989). Mean current speed in this study ranged from 5.3 to 13.8 cm s^{-1}, with maxima ranging from 11.2 to 40.0 cm s^{-1}. Judge et al (1972) found that near-bottom speeds from 4 to 11.3 cm s (maxima of 13 to 27.4 cm s^{-1}) did not affect growth of hard clams. Speeds > 10 cm s^{-1}, and potentially up to 30 cm s^{-1} appear to result in maximum growth, whereas speeds >30 cm s^{-1} are likely inhibitory due to frictional drag forces on the siphons and interference of bedload sediment transport on feeding (reviewed by Grizzle et al. 2001). Because seston concentrations and current speeds vary concurrently, the latter alone are not a good predictor of growth of clams in nature (Grizzle and Lutz 1989). Limited information is available on the effects of turbulent flow on *M. mercenaria*, as may occur most notably during storms in a shallow system, and/or in the proximity of bulkheads. Changes in the configuration of the inlets due to storm and hurricane events (or dredging activity and jetty construction) can greatly affect circulation patterns as well as the bottom topography within the bay, thus affecting bivalve populations. Most notably, the occurrence of Hurricane Sandy in November 2012 caused breaching of the barrier island system at Mantoloking in northern Barnegat Bay. This constantly shifting bottom topography from year to year, the short-term changes in current velocities with tide and wind in this shallow system, amd the complex circulation patterns generated by marsh islands [illustrated by Carriker (1961) and Chant et al. (1997) in Lower Little Egg Harbor], make it difficult to characterize localized flow conditions relevant for hard clams populations in nature. Chant et al.’s study (1997, see also Kennish 2001) shows that water circulation patterns and current velocities in Lower LEH are greatly influenced by the proximity to the inlet: during flood tide incoming current velocities dissipate rapidly moving northward from the inlet, with maximum velocities varying two orders of magnitude between the southern reaches and upper LEH.

Conclusions:

- Water current velocities are unlikely to limit hard clam distribution within the BB-LEH system except in localized areas, e.g., near bulkheads where wave action can erode the bottom and generate turbulent flow, and in areas of exceptionally high (e.g. near inlets) or very low current speeds that inhibit pumping rates or reduce the food supply respectively.

2b.vi. Nutrients

Biotic responses to nutrient loading are highly variable among estuarine types (Cloern 2001). For example, coastal lagoons of the mid-Atlantic region appear to respond differently to nutrient loading than larger, drowned-river valley systems such as Delaware Bay and Cheasapeake Bay (Glibert et al. 2007). The BB-LEH was classified as highly eutrophic by Kennish et al. (2007) based on application of NOAA's National Estuarine Assessment (NEEA) Model (Bricker et al. 1997, 1999) More recent analysis of diatom assemblages and organic N in sediment cores collected at up-bay marsh sites along a N to S transect provide further evidence of N-eutrophication in the BB-LEH system (Velinsky et al. 2011). Even at the southernmost site in LEH, there was evidence of an increase in organic N starting in the early 1990s. Organic nitrogen (particulate + dissolved) is the dominant form of N in the water column, with concentrations ~10x times greater than dissolved inorganic nitrogen (DIN) (Seitzinger et al. 2001).

Biotic parameters commonly used as indicators of eutrophication in the estuary include low DO, excessive micro- and macroalgal growth (total Chlorophyll *a* and % macroalgal cover respectively), biomass of epiphytic microalgae, harmful algal blooms (e.g., brown tides), altered benthic invertebrate communities (e.g. increase in opportunistic, infaunal deposit-feeding species), and loss of essential habitat (i.e., SAV) (Kennish et al., 2007, 2010; see sec. 4b). Recent proliferation of noxious sea nettles (*Chrysaora quinquecirra*) in the northern, lower salinity reaches of the estuary are also often cited as evidence of eutrophy and of changes in trophic structure. Eutrophication has also been attributed a role in the loss of shellfish beds in BB-LEH, but there is insufficient information to establish this link.

Not all abiotic and biotic parameters used as indicators of eutrophication in BB-LEH have been measured simultaneously and there are temporal gaps in the archived database which make it difficult to interpret long-term trends. Thus, measurements of total nitrogen (TN), DO, temperature, and turbidity/Secchi depth were obtained from 1989-1991 and 1993-2011. Nitrate plus nitrite (NO_3^- + NO_2^-), ammonium (NH_4^+), and phosphate (PO_4^3) concentrations were measured in the estuary from 1989-2011, but TP levels were only collected from 1999-2011. Biotic variables have been collected much more sporadically: e.g., Chl *a* measurements were recorded from 1997-2011, SAV metrics and macroalgal % cover were recorded from 2004-2006 and 2008-2011. *Aureococcus anophagefferens* concentrations were determined in 1995, 1999-2002, 2005, and only at one site in 2010 (see sec. 3b).

Because the BB-LEH Estuary is shallow, has a relatively long residence time, and bordered by a highly developed watershed, it is particularly susceptible to nutrient loading. The largest relative contribution of total nitrogen (TN) to the estuary is derived from nonpoint sources: surface runoff from the watershed (54% and 62% of the total load in 1998 and 2007 respectively), followed by atmospheric deposition (34% and 22% in 1998 and 2007 respectively), and most of the remainder contributed by direct groundwater discharges (Wieben and Baker 2009). This increase from surface water runoff over ~ 10 yrs. suggests that continued development and land alteration of the BB-LEH watershed likely play significant roles in nitrogen enrichment of the estuary. These TN load estimates were based on a measure of both DIN (NH_4^+ + NO_3^- + NO_2^-) and DON species in major river basins and represent estimates of the TN load delivered from the watershed to the receiving estuarine waters estimated by applying the NLOAD model described by Bowen et al (2007). The ratios between TN and TP loads (Table 1) are thus not representative of the nutrient ratios in the water column. Stormwater runoff (not measured in 1998), contributed 4% to the TN load in 2007. Because nitrogen inputs from sediments, and tidal influx were not included in these calculations, the TN load is considered to be an underestimate (Kennish et al. 2007). No major nitrogen point source inputs exist in the BB-LEH watershed. Since 1980, all treated wastewater from the Ocean County Utilities Authority's regional wastewater treatment system has been discharged 1.6 km offshore in the Atlantic Ocean. We are unaware of any study that examined the effect on salinity or on nutrient concentrations in the estuary of this alteration of the wastewater discharge, which occurred between the mid-70s and 1980.

Due to the spatially variable degree of urbanization and land use, the BB-LEH estuary exhibits a generally north to south spatial gradient in eutrophication, as illustrated by total nitrogen (TN) concentrations measured over a 20-yr period (1989 to 2009) (Kennish and Fertig 2012; Fig. 9). Thus, as a result of a north-to-south decrease in population density and watershed development, nutrient loading is highest in the northern segment of the estuary (Hunchak-Kariouk and Nicholson, 2001; Seitzinger et al., 2001; Wieben and Baker, 2009). These observations have been corroborated by extensive nutrient sampling and analysis conducted by the New Jersey Department of Environmental Protection (NJDEP) during the past decade. There is also a spatial gradient in nitrogen forms, such that inorganic nitrogen is more dominant in the northern sector of the estuary and organic nitrogen in the southern reaches. It is important to note that N speciation (e.g. organic vs. inorganic forms), nutrient availability, and nutrient ratios (N/P/Si) can play a key role in driving changes in the phytoplankton community.

Mean TN concentrations for the 1989-2009 period also exhibit strong seasonal patterns (Kennish and Fertig, 2012; Fig. 9). Highest TN values (>40 µM) occur during the summer, from June through September, in both central and southern segments of the estuary. Nutrient (particularly nitrogen) loading has been attributed a major contributing role to the greater incidence of algal blooms and macroalgal and epiphytic growth which have caused shading of seagrass beds (Kennish and Fertig 2012).

Hard clams exhibit mortalities and reduced growth when exposed to 880 mg NH_4^+ L^{-1} and 2,415 mg NO_3^- mg L^{-1} (Epifanio and Srna 1975), but these concentrations are much higher than those found in the natural environment, even in highly N-enriched estuaries (Nixon et al. 2001).

Analysis of growth of *M. mercenaria* juveniles and adults in Cape Cod, MA, estuaries spanning the range of TN-loads common to Atlantic coastal estuaries indicated that increasing N-eutrophication was positively related with microalgal biomass measured by suspended Chl *a* concentrations (up to levels of ~25 µg L^{-1}) and estimated phytoplankton Carbon levels

(Carmichael et al. 2004) (Fig. 10). This increase was associated with an increase in shell and tissue growth of hard clams up to high phytoplankton C levels of up to 1,100-1,300 µg L^{-1}, suggesting that *M. mercenaria* grows well under eutrophic estuarine conditions. This study recognized, however, that negative effects of N-eutrophication might result from low sediment DO levels. More importantly, the authors' analysis only took into consideration the effects of food quantity as measured by these bulk parameters, but did not consider changes in phytoplankton composition that may result from N-enrichment (see sec. 3).

Conclusions:

- There is no evidence that high, bulk nutrient levels in BB-LEH (e.g. TN loads) have directly affected the hard clam population in either a negative or positive fashion. The most eutrophic areas occur in northern reaches of Barnegat Bay where hard clams are restricted due to lower salinity.
- Evidence from other US Atlantic estuaries indicates that hard clams grow well at high levels of phytoplankton biomass (~ 30 µg L^{-1}). Microalgal quality (phytoplankton size structure and species composition) is thus more likely to be important in affecting clam production that algal quantity, as measured by Chl *a* concentrations. The effects of absolute and relative nutrient concentrations on the phytoplankton community and their possible effects on algal quantity, quality and harmful algal blooms are discussed in sec. 3 below.

3. Seston and the BB-LEH phytoplankton community: food quantity and quality for hard clams

3.a. Phytoplankton spatial and temporal patterns

The BB-LEH estuary is a highly productive system, in which annual phytoplankton production approaches 500 g C m^{-2} yr^{-1}, and is comparable to that of Great South Bay, NY, at ~450 g C m^{-2} yr^{-1}, a coastal lagoon that once sustained thriving populations of *M. mercenaria* (reviewed by Styles et al. 1999). Algal primary production in these two systems is ~ twice as high as that of Great Bay, NJ, and also higher than that of other Atlantic coastal lagoons, such as the Chincoteague Bay, MD (~170 g C m^{-2} yr^{-1}). Mean Chl *a* concentrations in the BB-LEH estuary show maximum values during the summer months (Olsen and Mahoney 2001). Despite evidence of increasing eutrophication in the system (sec.2.b.vi), there was no apparent increase in the mean summer Chl *a* concentrations reported in Manahawkin Bay between 1988 and 1998 by Olsen and Mahoney (2001) (mean values ranged from 11.2 to 26.4 µg L^{-1}) (Fig. 11A). Similarly, mean summer Chl *a* concentrations determined at NJDEP's water quality monitoring stations in LEH, Manahawkin Bay and Barnegat Bay between 1999 and 2010 did not show an increasing trend over the years (Fig. 11B). This is consistent with findings that annual TN and DIN loading are not significantly related to Chl *a* in Atlantic coastal lagoons (Seitzinger et al. 2001).

Generally, maximum phytoplankton production and biomass within BB-LEH occur in the northern part of the estuary where highest nitrogen levels have been recorded (Seitzinger et al. 2001), but high Chl *a* levels with summer maxima of up to 36.6 µg L^{-1} also occur in the Manahawkin Bay area (Olsen and Mahoney 2001, see also Fig. 12). Chlorophyll *a* is the parameter that is routinely used in monitoring programs to provide a synoptic view of the temporal and spatial variation in algal biomass levels. Chlorophyll *a* concentrations show more pronounced spatial gradients within BB-LEH during the summer months than during the spring and fall (Fig. 12). Chlorophyll *a* measurements alone often provide an insufficient measure of the available food supply for suspension-feeding bivalves. Food quality, as measured by the size structure and/or species composition of the phytoplankton can have more profound effects on the reproductive output of hard clams (Newell et al. 2009), and growth of larval and juvenile hard clams than food quantity (reviewed by Bricelj 2009).

Shifts in the phytoplankton community associated with eutrophication of coastal bays can thus have serious long-term effects on higher trophic levels, including commercially valuable shellfish. Proliferation of a number of harmful algal bloom (HAB) species has occurred in mid-Atlantic shallow bays: brown tides in SSE and BB-LEH, blooms of *Cochlodinium polykrikoides* in the Peconic Estuary, NY (Gobler et al. 2008), and most recently, since 2006, annually recurring red tides caused by *Alexandrium fundyense*, producer of paralytic shellfish toxins, in the Huntington-Northport Estuary, NY (Hattenrath et al. 2010). Blooms of *Cochlodinium heterolobatum* were reported over ~ 20 km in BB-LEH in 1964, causing mortalities of crabs, mollusks and small fish (Mountford 1965), and the DSP producers *Dinophysis acuta*, *D. acuminata* and the benthic *Prorocentrum lima* have been reported in low densities in BB-LEH (Mountford 1984, Olsen and Mahoney 2001). It is important to note that there are to date no known cases of shellfish contamination by microalgal toxins of public health concern in the BB-LEH ecosystem. The dinoflagellate, *Prorocentrum minimum*, thrives under eutrophic conditions in estuaries, and is favored by organic nitrogen enrichment (Heil et al. 2005). This species (var. *triangulatum*) was known to be abundant, causing water discoloration (red tides) in BB-LEH in the past, e.g., in 1966 (Mountford 1967) and in 1997 and 1998 (Olson & Mahoney 2001). Table 3 lists examples of microalgal species that have been documented in BB-LEH in the past and are potentially toxic and/or known to be a poor food source for hard clams.

Changes from diatom/dinoflagellate dominance to greater abundances of microflagellates, small chlorophytes and the bloom-forming *A. anophagefferens* have been shown to play a role in the reduction in shellfish resources, such as bay scallops, *Argopecten irradians*, and hard clams, *M. mercenaria* in Long Island, NY, bays (Bricelj and Lonsdale 1997). As primary consumers, suspension-feeding bivalves are particularly vulnerable to changes in phytoplankton species composition, and in turn, when abundant, they can locally alter the phytoplankton species composition and size structure in shallow estuaries. Thus, a reduced population of suspension-feeders reduces grazing pressure during early stages of brown tide development and may play a significant role in retarding or preventing the development of algal blooms (Cerrato et al. 2004).

Recent short-term studies indicate that there are strong spatial gradients in food quality/quantity across Long Island SSE, NY, and Sandy Hook Bay, NJ, during years of no or low brown tide. These are associated with marked differences in hard clam gonadal production (reviewed by Bricelj 2009). The relative contribution of small algae (< 5 µm) to total phytoplankton biomass, and algal species composition were found to be especially useful in characterizing the food supply for hard clams. Long term monitoring programs typically do not include these measurements. Therefore long-term patterns (e.g. a shift towards dominance by picoplankton, PP (typically defined as planktonic organisms in the size range of ~0.2 to 2 µm) that may relate to eutrophication and/or climate change in these estuaries remain unknown. Additionally, modeling (Hofmann et al. 2006) and empirical data have shown that the food supply for benthic suspension-feeders such as *M. mercenaria* remains ill-defined, and larval model simulations showed that variation in food quality had much greater effects on hard clam larval metamorphic success than changes in temperature and food quantity (Bricelj et al. 2009).

The BB-LEH is characterized by summer blooms of coccoid, picoplanktonic microalgae ("small forms") such as the chlorophyte *Nannochloris atomus* and cyanobacterium *Synechococcus sp*. (Olsen and Mahoney 2001). These are poorly captured and digested by post-settlement hard clams (Bricelj et al. 1984), and caused the decline of oysters in GSB in the 1950s (Ryther 1954). In contrast to juvenile and adult hard clams that show an exponential decrease in particle retention efficiency by the gills below ~ 3-4 µm, *M. mercenaria* larvae can readily capture and ingest picoplanktonic algae (reviewed by Grizzle et al. 2001). Thus, in contrast to the ribbed mussel, *Geukensia demissa*, a common inhabitant of salt marshes in BB-LEH, hard clams are not effective in capturing bacterial-sized particles. Another "small form" (cell size below the 100% retention capture of the hard clam gill) that can occur in BB-LEH at high summer concentrations, although typically lower than *N. atomus* and *A. anophagefferens*, is the diatom *Minutocellus polymorphus* (Olsen and Mahoney 2001). Peak densities of picoplankters rarely coincided with Chl *a* maxima in the system, and Chl *a* summer levels were higher in the upper bay (up to 33-36 µg L^{-1}) than in the lower bay where picoplanktonic blooms were more prevalent. Picoplanktonic blooms were typically more widespread, began earlier (mid- to late June) and lasted longer (to early October) in southern BB-LEH areas than in central and northern areas. Development of these blooms was associated with temperatures >20^{o}C, and peak levels were attained at >25^{o}C (Mahoney et al. 2006).

<u>Conclusions:</u>

- High-density (up to 10^5 to 10^6 cells ml^{-1}) summer blooms of picoplanktonic microalgal species (e.g. *Nannochloris atomus*, *Aureococcus anophagefferens*) are characteristic of the BB-LEH ecosystem. These can be a poor food source for hard clam production due to production of toxic metabolites, small size and thus poor capture by the clam gills, and/or poor digestibility/absorption.
- Food quality is often found to be a more critical determinant of hard clam growth than food quantity. Measurements other than total phytoplankton biomass (total Chl *a*), are necessary to determine the available food supply for hard clams, and the response of phytoplankton to eutrophication and other environmental stressors.

3.b. Brown tide

Mid-Atlantic coastal lagoons, including BB-LEH, have experienced recurrent brown tides of the picoplanktonic pelagophyte *Aureococcus anophagefferens* (Mahoney et al. 2006, Wazniak and Glibert 2004, Trice et al. 2004, Bricelj 2009) (Fig. 13) Brown tides have also occurred in Great Bay, NJ, Little Assawoman Bay, DE, and extend as far south as the MD coastal lagoons (Chincoteague Bay). The presence of *A. anophagefferens* in BB was first confirmed by Anderson et al (1989) who determined by immunofluorescence a low density of 400 cells ml^{-1} in a single archived sample from September 1986. This method is required as light or epifluorescence microscopy is inadequate to distinguish *A. anophagefferens* from similar sized, chloroplast-containing algae (Sieburth et al. 1988).

Blooms of *A. anophagefferens* were first identified by immunofluorescence in BB-LEH in 1995 when peak densities exceeded $1x10^6$ cells ml^{-1}, and occurred at densities of ~1.5 to 2.5 x 10^6 over four consecutive years between 1999 and 2002. More moderate cell densities (≤ 200,000 cells ml^{-1}) were documented in 1988, 1997, 2003 and 2004, but routine monitoring for brown tide in BB-LEH ceased after 2004. Peak densities in mid-Atlantic estuaries typically occur between mid-May and early June, thus coinciding with the period of major spawning of *M. mercenaria* at this latitude. Secondary, lower-intensity blooms can also occur in the fall, and may affect the clams' ability to accumulate energy reserves for overwinter survival or as a precursor for gametogenesis in the spring. In BB-LEH brown tide typically developed in mid-May and peaked in June, several weeks earlier than other dominant picoplankters such as *N. atomus* which peaked in August and early September (Olsen and Mahoney 2001). Moderate cell densities of brown tide of up to 158,000 cells ml^{-1} were determined, however, in Aug. 2010 in LEH (Wei et al. 2011), and densities up to 5,300 cells ml^{-1} were confirmed by immunofluorescence in LEH and lower Barnegat Bay in the first 2 wks of July 2012 (L. Ren, Academy of Natural Sciences of Drexel University, PA, pers. comm.).

A commercial shellfish hatchery in Tuckerton, LEH (previously Biosphere Inc., now Parson's Mariculture LLC), reported mortalities of larval hard clams and growth arrestment of juveniles for up to 2 months (May to June) during 1995, 1997 and 1999 brown tides. Weekly sampling at this facility during the summer of 2005 and 2006 found levels of up to 47,000-67,000 during these two consecutive years (Fig. 14). For this study, 4 juvenile *M. mercenaria* size classes (n = 5 clams per size class; mean initial SL = 2, 8, 3.5, 6.9 and 9.1 mm) were held in an upweller system with flow-through ambient seawater. There is some evidence of a drop in growth rate associated with the peak brown tide event in 2006 when *A. anophagefferens* attained 67,000 cells ml^{-1}. Weekly shell growth declined by 28, 22, 31and 41% for the 4 size classes respectively, whereas at another hatchery site near Atlantic City, NJ, outside of the BB-LEB system without brown tide, clams experienced an increase in SL (28, 61, 29 and 8% for the 4 size classes respectively). When brown tide reached ~40,000 cells ml^{-1} in late August/early September growth rates of juveniles at the Tuckerton facility were again suppressed, but they also dropped at the southern NJ site without brown tide. Salinity and temperature declined at both sites suggesting that any potential effects of brown tide were masked by the passage of a cold front. In 2005 clams experienced a progressive reduction in growth rates during the study period that cannot be clearly related to brown tide levels.

A laboratory study showed that addition of 400,000 *A. anophagefferens* cells ml^{-1} to an optimum baseline diet of 60,000 *Isochrysis galbana* (clone T-Iso) cells ml^{-1} completely suppressed growth of juvenile hard clams, whereas addition of an order of magnitude lower *A. anophagefferens* concentration (= 80,000 cells ml^{-1}), more comparable to peak levels described in the LEH field study above, resulted in a significant reduction in growth relative to the unialgal control diet of 60,000 *I. galbana* cells ml^{-1} (Bricelj and McQuarrie 2004). Feeding inhibition of juveniles occurred at *A. anophagefferens* densities ≥35,000 cells ml^{-1} (Bricelj et al. 2001), and deleterious effects of growth of hard clam larvae can occur at densities as low as ~50,000 cells ml^{-1} that do not cause discoloration of the water column (Bricelj and MacQuarrie 2007). Toxicity of an *A. anophagefferens* strain (CCMP 1794) isolated from BB in 1997 was confirmed via a bioassay which measures the reduction in clearance rate of juvenile mussels, although its toxicity was lower than that of a Long Island isolate (Bricelj unpubl.).

Typically *A. anophagefferens* concentrations increase from north to south in the BB-LEH system. The greatest prevalence and intensity of brown tide has occurred in the southern half of the bay, including lower Barnegat Bay and LEH (Olsen and Mahoney 2001, Mahoney et al. 2006; Fig. 15). This spatial distribution is based on sampling in years of brown tide occurrence when both BB and LEH were monitored, e.g. 1995 and 1999 to 2002, and *A. anophagefferens* concentrations were confirmed by immunofluorescence. In the BB-LEH estuary Category 3 blooms (as defined in Fig. 15) occurred during months when the mean water temperature exceeded 14^{o}C, and the mean salinity ranged from 26 to 31^{o}C, but these conditions did not guarantee the occurrence of brown tides (Pecchioli et al. 2006). These authors also found that brown tide (especially at levels > 200,000 cells ml^{-1}) was associated with reduced monthly mean freshwater discharge from the Toms River (< 200 ft^3 sec^{-1}, DON concentrations > 11 µmol L^{-1} and monthly mean Secchi disk depths < 1 m). During the 1999 brown tide which was monitored more extensively both temporally and spatially, Great Bay showed reduced bloom persistence and intensity relative to the BB-LEH estuary. This may be partly attributed to the former's higher flushing rate and less eutrophic condition (Mahoney et al. 2006). *Nannochloris* and *Stichochoccus* have a wide salinity tolerance (Ryther 1954), whereas *A. anophagefferens*, grows best at relatively high salinities, ranging from 24 to 33 (LaRoche et al. 1997), and shows optimal growth at ~ 30 (Cosper et al. 1987).

In the BB-LEH system, salinity was attributed a more important role than water temperature in explaining the interannual (e.g. 1998 vs. 1999) and spatial variability in the development of brown tide (Mahoney et al. 2006). Temperature, however, was considered an important contributing factor to seasonal abundances of *A. anophagefferens* in BB-LEH, as growth of this species is favored by temperatures in the range 12 to 25^{o}C, but inhibited at temperatures >27^{o}C.

Brown tide causes light attenuation and can thus have deleterious effects on SAV. Secchi depths were reduced to 0.3 to 0.4 m during peak brown tide conditions in the BB-LEH (Mahoney et al. 2006). Brown tide has been associated with reduced DIN from groundwater during dry years (Laroche et al. 1997), and both field and laboratory studies indicate that *A. anophagefferens* preferentially uses DON over inorganic N forms (e.g. Berg et al. 1997, Gobler et al. 2005), and has thus been proposed as an indicator of organic N-based eutrophication (Glibert et al. 1997). Picophytoplankton (PP) in general has been recommended for inclusion in eutrophication assessments (Gaulke et al. 2010), and both PP biomass and primary productivity are often found to be high (~ 40% of Chl *a*) in shallow, eutrophic estuaries with long residence times and warm summers that promote nutrient regeneration from sediments. The potential for warming of shallow estuaries induced by climate-change may also promote the dominance of PP in these estuaries.

Conclusions:

- Since routine monitoring of *A. anophagefferens* was discontinued after 2004, the impact of brown tide on recruitment of suspension-feeding bivalves (hard clams and oysters) in the BB-LEH system in recent years remains unknown.
- Brown tides of *A. anophagefferens* peak in summer in BB-LEH and are generally more prevalent, last longer and attain higher densities in the southern, higher salinity portions of the BB-LEH.
- Brown tide causes concentration-dependent growth inhibition of hard clams at both larval and juvenile stages, and can potentially cause reduced reproductive effort of adults. These deleterious effects occur at concentrations that do not cause discoloration of the water.

3.c. Turbidity and total suspended solids (TSS = seston)

Soft-tissue growth of juvenile *M. mercenaria* is significantly reduced at suspended sediment concentrations >25 mg DW l^{-1} (Bricelj et al. 1984). Thus their growth is expected to be reduced in muddy, sediment where bottom resuspension can exceed this concentration threshold. Turbidity, as measured by Secchi depth readings, is typically ~ 1m in Barnegat Bay and lower in the northern part of BB where watershed development and nutrient loading are greatest (Seitzinger and Styles 1999). Hard clams eggs and larvae were relatively tolerant of high suspended sediment levels. Eggs suffered increasing abnormal development at silt concentrations ≥750 mg l^{-1}, and growth of larvae was inhibited above this threshold silt concentration (reviewed by Roegner and Mann 1991). There is limited information on near-bottom TSS concentrations in BB-LEH that are relevant to assess their potential effects on growth of clams, as monitoring is typically based on measurements in surface waters. These concentrations are generally expected to be higher above fine-grained due to increased sediment resuspension, than above coarse sediments. A 2012 study conducted from early June to mid-September showed that concentrations of particulate inorganic matter (PIM, a measure of resuspended sediments, which averaged from 49 to 72% of TSS at 4 stations in BB-LEH) determined 20 cm off-bottom in Tuckerton Cove (over muddy substrate) consistently remained below 20 mg DW L^{-1} (Bricelj et al. unpubl. data from NJDEP-sponsored research). Even lower PIM concentrations were found above sandy substrate. These levels are thus not expected to inhibit growth of hard clams. Seston concentrations measured at the surface and 30 cm off-bottom in 2011/2012 are shown at selected sites in BB and LEH in Figure 16. Median TSS concentrations typically remained below 20 to 30 mg L^{-1}, and were consistently higher off-bottom than at the surface. Intensive, hourly sampling over 24 h showed considerable tidal variation in TSS concentrations especially off-bottom, with episodic peaks exceeding 50 mg L^{-1} (Helen Pang, NJDEP unpublished data). Episodic storm events may also lead to transient spikes in water column turbidity and even burial of clams.

<u>Conclusions</u>:

- Data on near-bottom TSS or PIM concentrations are relatively sparse, but generally values in the BB-LEH system do not appear to be limiting to hard clam growth and distribution. It is possible that localized areas with continually high near-bottom TSS levels might be identified, and these could be important in establishing areas for restoration activities.

4. Bottom characteristics: sediment type, submerged aquatic vegetation (SAV) and benthic macroalgae

4.a. Sediment

A map characterizing bottom sediments in the BB-LEH estuary based on a detailed, comprehensive study (Psuty 2004) is shown in Figure 17. Coarser and sandier sediments generally occur on the eastern margin of the estuary and towards the inlets. Finer-grained sediments are more prevalent towards the mainland and occur especially in the low-energy, narrower portions of the bays. These data were obtained ~ a decade ago, and changes may be expected. For example, muddy bottom currently characterizes the margins of the salt marshes in

Tuckerton Cove (Bricelj, personal observation). Bottom sediment characterization undertaken as part of a benthic survey conducted in BB-LEH in 2011/2012, will allow comparison with this previous study. Great Bay shows a marked gradient in sediment type from predominantly sands in the eastern sector to generally finer-grained sediment along the western margin (Kennish et al. 2004).

Sediments are a resource that is required if salt marshes are to accrete vertically. The current configuration of BB-LEH estuary, and especially the salt marsh wetlands along its southwestern margin, are increasingly threatened by increased sea levels associated with climate change. During the 20th century globally averaged sea level rise was ~ 1-2 mm yr^{-1}, but climate change predictions indicate that this rate will accelerate in future at estimated rates of 3 to 5 mm yr^{-1}, depending on the predictive model used (Day et al. 2008). Sedimentation on these salt marshes is at or just below the rate of current rate of sea level rise in the estuary (Velinsky et al. 2011), and the latter is expected to increase at a faster rate than sediment supply in the coming decades. Since these wetlands play a major role in nutrient control, as they sequester 79% of the N and 54% of the P entering the estuary from upland sources, they are important in control of primary production and possibly harmful algal blooms. Because lagoonal systems do not typically receive as much sediment as river dominated estuaries, the fringing marshes in the lagoons are expected to migrate rather than accrete vertically. The rise in sea level, under normal conditions would thus cause a landward migration of marshes on the western shore, and a westward migration due to barrier island migration on the eastern shore. Man's occupation of the shore has blocked these processes and thus the low levels of sediment input will particularly threaten marshes in this and similar lagoonal systems.

Mercenaria mercenaria are substrate generalists and occur in a variety of substrate types from mud to sand. Their growth, however, is typically reduced in fine-grained, muddy bottom compared to sandy sediments (reviewed by Grizzle et al. 2001). While bottom sediment grain size is generally directly correlated to the flow regime, Grizzle and Morin, (1989) and Grizzle and Lutz (1989), in a transplant experiment, found that in general site flow characteristics (horizontal flux) were more important than sediment type in influencing the growth of hard clams. In addition, sediment characteristics appear to affect the survival of newly recruited hard clams in that sediments with some component of shell are known to have higher densities of clams. This is because heterogeneous sediment with mixtures of coarse particles has been shown to reduce the effects of crustacean predators (reviewed by Kraeuter, 2001), and act as a buffer to low pH in fine-grained sediments (Green et al. 2004, 2009).

Low pH may occur, however, in fine grain sediments leading to calcium carbonate undersaturation and erosion of the aragonitic shell of newly settled hard clams <1 to 2 mm, thus contributing to mortalities during this vulnerable life history stage (Green et al. 2004, 2009). When *M. mercenaria* seed clams (0.2 to 0.6 mm SL) were placed in containers filled with natural fine-grained, silt/clay sediment which had pH adjusted from ambient (air) pH = 7.9 , and other containers with pH adjusted with the use of carbon dioxide to pH 7.0 and 7.3, they found significant shell erosion and size-dependent mortalities (>90% within 12 d in the smallest size class) at the lower pH values (Green et al. 2009). These authors found that addition of ground bivalve shell to buffer the low pH of muddy natural sediment was effective in mitigating these mortalities in *Mya arenaria*. Thus shelling of the bottom can enhance clam recruitment (Kraeuter et al. 2003) either through the process of buffering and/or predator reduction.

Conclusions:

- Sediment characteristics influence recruitment and growth of hard clams. Generally, clam abundance is higher in heterogeneous sediments with some shell or gravel components (see. sec. 8).
- The sedimentary characteristics do not change much on a bay-wide basis and over time unless induced by anthropogenic change (dredging, bulkheading, increase in erosion due to loss of wetlands, etc).
- The long term trends in sediment characteristics in BB-LEH will be dominated by sea-level rise, but bivalves such as *Mercenaria mercenaria* and *Crassostrea virginica* can provide a locally dominant source of carbonate (shell) to sediments. The suppression of these species from large parts of the estuary could affect the sedimentary carbonate budget and bivalve recruitment rates.
- Enhancement of sediments with shell (calcium carbonate) in restoration areas, particularly where little shell is currently found, should be evaluated as part of the restoration process.

4.b. Submerged aquatic vegetation (SAV)

It is likely that the BB-LEH suffered nearly complete elimination of eelgrass (*Zostera marina*) during the epizootic that affected most of the northeast and mid-Atlantic coast in the 1930s. Thus the current distribution reflects the recovery from the *Labyrinthula* spp. induced wasting disease (Muehlstein et al. 1991). Whereas recent declines can be attributed to other factors, some disease related mortality cannot be ruled out.

Approximately 75% (>6,000 ha) of the seagrass beds in NJ occur in the BB-LEH estuary, where they are largely concentrated in shallow subtidal waters (< 2m) with sandy sediments along the eastern margins of the estuary (Fig. 18). Although both eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*) co-exist in BB-LEH, the former is far more abundant accounting for >99% of the total areal coverage of seagrass habitat in the system, and dominates in central and southern sectors of the bay, whereas *R. marina* is dominant in the less saline northern portion of the bay (Lathrop and Haag 2011). Seagrasses provide multiple ecosystem services. They provide a vital habitat for numerous organisms, are a major source of primary production, serve to stabilize bottom sediments, play an important role in the biogeochemical cycling of elements, and provide sensitive indicators of estuarine water quality and long-term ecosystem health (Wazniak et al. 2007). They serve as Essential Fish Habitat and support many commercially and recreationally important shellfish and finfish species such as bay scallops (*Argopecten irradians*), mussels (*Mytilus edulis*), blue crabs (*Callinectes sapidus*), and weakfish (*Cynoscion nebulosus)*, which use the beds extensively during at least a part of their lives.

A major decline in biomass and % SAV cover has been reported in some sectors of the BB-LEH estuary since the 1970s. Bologna et al. (2000 and 2001) documented marked losses of *Zostera marina* cover in LEH during the summer of 1998. Lathrop and Bognar (2001) and Lathrop et al. (2001) noted a loss of ~2,000 ha of seagrass in the estuary between 1987 and 1999, representing a ~25% reduction of seagrass habitat. However, color imagery obtained via overflights in 2003, complemented with boat-based surveys throughout the estuary, revealed that seagrass distribution in BB-LEH remained relatively stable between 1998 and 2003 (Lathrop et al. 2006). The apparent (15%) decline of seagrass beds between the late 1990s and 2003 was thus attributed to different mapping techniques rather than to actual seagrass losses. A significant loss of seagrass may have occurred in the deeper waters of the estuary between the 1960s and 1990s, resulting in the contraction of the beds to shallower subtidal flats (Lathrop et al. 1999, Bologna et al. 2000, Lathrop and Bognar 2001). Boat traffic and wasting disease have likely exacerbated SAV losses attributable to nutrient overenrichment of the estuary.

A 4-year (2004-2006, 2008) study of seagrass demographics in 4 disjunct BB-LEH beds revealed an ongoing decline in plant biomass (g dry weight m^{-2}), shoot density (shoots m^{-2}), blade length, and percent cover of bay bottom (Kennish et al. 2010). This was attributed to increasing eutrophication, resulting in light attenuation by phytoplankton and epiphytic microalgae. *Zostera marina* is very sensitive to light limitation and its depth distribution is approximately equal to Secchi disk depth (Dennison et al. 1993). Of all the metrics analyzed in the Kennish et al. (2010) study, seagrass biomass showed the most significant decrease over the 2004-2006 study period. This decline was evident estuary-wide, but was most pronounced in Little Egg Harbor, where the mean aboveground and belowground SAV biomass declined by 88% and 59% respectively between 2004 and 2006. The progressive seasonal reduction in the percent cover of seagrass in the estuary apparent during this study correlated well with diminishing eelgrass biomass. Percent cover was reduced from 45%-21% in 2004, to 32%-19% in 2006, a year characterized by unusually high mid-summer temperatures, and this distribution was comparable in 2008. A comparison of eelgrass conditions in 2004-2006 with those in 2008-2010 showed that aboveground biomass of *Z. marina* showed a significant, estuary-wide decline, although a parallel decline in % areal cover or shoot density was not detected (Fertig et al. 2013).

In the BB-LEH eelgrass densities over the 2004-2006 study period attained a maximum mean value of 378 shoots m^{-2} in June-July 2006 and declined seasonally thereafter to 164 shoots m^{-2} by November (Kennish et al. 2010). Over the 2008-2010 study period, peak summer eelgrass densities were relatively higher, averaging 475 shoots m^{-2} (range = 347 to 665 shoots m^{-2}) (Fertig and Kennish 2013). Blade length and thus eelgrass canopy height attained a maximum of 34 cm (2004-2008) and 29 cm (2008-2010).

Unlike bay scallops, *M. mercenaria* are not restricted to SAV meadows during their early life history, although they commonly occur within eelgrass beds in sediments mainly composed of silty sand in coastal lagoons, including the BB-LEH estuary. Eelgrass beds can have both positive and negative effects on *M. mercenaria* populations depending on their grass density. Positive effects of eelgrass habitat in promoting hard clam growth and survival can include protection from predators due to increased structural complexity that prevents burrowing by common predators (Blundon and Kennedy 1982), reduced interference of clam feeding by siphon nipping fish, sediment stabilization and thus reduced sediment resuspension that inhibits clam growth rates, utilization of locally-generated near-bottom food source (e.g. benthic diatom resuspension) (Judge et al. 1993), increased food supply due to the baffling effect of SAV (Peterson et al. 1984) and fishing deterrence or reduction caused by gear obstruction. Negative feedbacks primarily result from reduced flow at high shoot densities leading to settlement of suspended particulates and thus reduced replenishment of the food supply.

In turn, suspension-feeding bivalves, including hard clams, can lead to positive feedbacks for eelgrass by increasing water clarity through their filtration activity and transfer of nutrients to sediments via biodeposition. These can lead to an increase in eelgrass productivity (e.g. Peterson and Heck 1999). Episodic, heavy settlement of mussels, *Mytilus edulis*, in BB-LEH especially in Barnegat Inlet, in 2003 resulted in a significant negative correlation between water column Chl *a* and mussel densities, which peaked at $> 170{,}000\ m^{-2}$ Bologna et al. 2005) These high densities in May-June were attributed a potential role in preventing development of brown tide that year.

Mesoscosm experiments also showed that filtration of *Aureococcus anophagefferens* cells at low densities by hard clams may prevent the development of brown tide outbreaks that cause severe light attenuation and reduce eelgrass production. Nutrient enrichment of sediments via bivalve biodeposition can facilitate eelgrass productivity given that *Zostera marina* absorb most of their nutrients from sediments via their roots rather than from the water column (Peterson and Heck 1999). Experiments conducted in mesocosms (300 L, 1.2 m depth) containing transplanted *Z. marina* shoots, filled with ambient seawater enriched with nutrients to simulate eutrophic estuarine conditions, showed that addition of *M. mercenaria* (52 mm SL) significantly increased eelgrass leaf growth over 12-18 d at clam stocking densities ranging from 14 to 57 clams m^{-2} (Wall et al. 2008). The highest clam density approximated the historical maximum attained in GSB. Eelgrass facilitation was largely linked to the reduction in light attenuation resulting from the clams' clearance of water column particulates relative to controls without clams.

Conclusions:

- Seagrasses do not constitute essential habitat for hard clams, as they do for early life history stages of bay scallops. A decline of SAV in the estuary is expected to have more subtle and less predictable ecological effects on hard clam populations, which may be positive or negative depending on flow conditions, SAV density, the composition of the predator assemblage, DO levels, etc. Thus, although SAV may provide a refuge for juvenile clams and thus enhance total standing stocks, there is no evidence indicating that declines or increases in SAV within the BB-LEH system will greatly affect hard clam populations.
- Areas with light cover of SAV might be excellent areas for rehabilitation efforts because human disturbance within those areas will be restricted, especially within the MCZ, although planting efforts could attract harvesters in other areas.
- Suspension-feeding bivalves, including *M. mercenaria*, at relatively high densities, can enhance SAV growth via filtration of suspended particulates and increase in water column light penetration.

4.c. Macroalgae

Benthic macroalgal blooms, used an indicator of eutrophic conditions in the BB-LEH, are detrimental to seagrasses as the mats formed cause severe light attenuation leading to SAV dieoff (Bologna et al. 2001, Kennish et al. 2011). Seaweed decomposition can additionally cause oxygen depeletion and high hydrogen sulfide concentrations in sediments. The dominant macroalgae are typically ephemeral, drifting forms and bloom most frequently during June, July and August, but can persist through November. Although the dominant species in the macroalgal community vary seasonally, the most common bloom-forming species in the BB-LEH are the sheet-like forming green alga *Ulva lactuca*, and several red macroalgae including *Spyridia filametosa*, *Gracilaria tikvahiae*, and *Champia parvula* (Kennish et al. 2010, 2011). In a survey conducted in BB-LEH in 2004, these species occurred in 59%, 55%, 30% and 23% of the samples respectively (Kennish et al. 2010). In 2005, *G. tikvahiae* was dominant (70% occurrence) followed by the red alga *Bonnemaisonia hamifera* (56%) and *S. filamentosa* (46%). Mean % macroalgal cover in seagrass beds in LEH and BB attained a maximum of ~38%.

Blanketing of the bottom by macroalgae is expected to be detrimental for bivalve-suspension feeders such as *M. mercenaria*. Reduced dry tissue weight was shown for adult *M. mercenaria* under heavy macroalgal cover in Delaware Inland Bays (Tyler 2007). Mats of green macroalge, *Ulva* sp. and *Enteropmorpha* sp. are well known to cause suffocation, reduce burial depth and growth inhibition of *Mya arenaria* in ME coastal waters (Auffrey et al. 2004). *Ulva* mats reduced DO concentration below 2 mg L^{-1} after about 20 h and caused cockles, *Austrovenus stutchburyi,* to migrate to the surface and, if the conditions persisted, the cockles eventually died (Marsden and Bressington 2009). Franz and Friedman (2002) found diurnal changes in DO below beds of *Ulva* in Jamaica Bay, NY, with zero DO concentrations present on many nights. All infaunal benthos including meiofauna such as copepods were reduced beneath the mats.

<u>Conclusions:</u>

- While macroalgal mats can cause clam mortality, adult hard clams can generally survive for considerable periods under low oxygen conditions. It is more likely that dense algal mats, because they are more prevalent in summer, would reduce recruitment and survival of post-settlement stages via suffocation and hypoxia. Heavy macroalgae cover can potentially reduce food availability of all life history stages.

5. Water Quality

5.a. Water quality classification in relation to shellfish harvest

Hard clams are suspension feeders that pump large volumes of seawater (Table 4) and as a result can contribute to ecosystem services by controlling microalgal biomass in shallow estuaries. Their high pumping rates also allow them to accumulate contaminants from the particulate material filtered from the water column that pose a health threat to human consumers. The water quality of growing waters thus poses a public health concern. The NJ DEP's Bureau of Marine Water Monitoring conducts surveys to evaluate shellfish growing waters based on levels of total and fecal coliform bacteria. These sanitary surveys form the basis for 4 classifications: Prohibited (waters condemned for harvest of oysters, clams or mussels), Special restricted (waters condemned for harvest of oysters, clams or mussels except for those that are either depurated or relayed under special permit), Seasonal (waters condemned for the harvest of shellfish, but open according to a schedule published by NJDEP and Approved (waters approved for the harvest of oysters, clams, or mussels) (Fig. 19). The area of the BB-LEH shellfish survey is covered from north to south by charts 6 to 10 (not shown but found at <u>http://www.nj.gov/dep/bmw/2012classcharts/2012classcharts.pdf</u>). Generally throughout the estuary shoreline areas and the creeks are Special Restricted or Seasonal areas and the center of the Bay and areas near the ocean inlets are open for harvest of shellfish. Most of the Special Restricted and Seasonally Approved areas are in or near sites that were developed for housing (much of which is seasonally occupied) and contain areas with large numbers of docks for pleasure craft. All public dock sites are deemed uncertified.

The area surrounding Toms River to Cedar Creek, where clams are mostly absent due to low salinity, is covered by Chart 6. The center of the bay and most of the eastern shore are open to harvest. Chart 7 covers the area of Lacey, Ocean, and Barnegat Township on the west and

Berkeley Township, Barnegat light and Long Beach on the east (township locations are shown in Fig.7). With the exception of Gulf Point, the western shore is mostly Special Restricted or Seasonal, while the center of the bay and the eastern side of the bay to Barnegat inlet are Approved for harvest. The area around Barnegat Light is a Special Restricted zone and the area of Long Beach is a Seasonal zone. Chart 8 covers the area from Barnegat Light to the Boro of Harvey Cedars on the east and parts of Barnegat and Stafford Township on the western shore. All the center of the bay and western shore is Approved for harvest while the area of Long Beach Township and Harvey Cedars is generally, with a few exceptions, Seasonally Approved. Chart 9 covers the area of Long Beach Township (Surf City, Ship Bottom, Brant Beach and Haven Beach) on the east and Stafford Township Bay Side and Eagleswood Township on the west. All the bay center and Stafford Township to the edge of Bay Side are Approved waters. On the east the entire shoreline is in the Seasonal Classification zone. Chart 10 encompasses most of LEH. In general the center of the bay is Approved, the eastern side of the bay through the end of Beach Haven Borough is Seasonally Approved and the area near the Beach Haven Inlet is Approved. On the western shore most of the Creeks are Special Restricted areas.

The monitoring program that provides for the above classification also does a complete intensive sanitary survey on a 12 year rotating schedule with interim evaluations, and reappraisals, completed on a three-year basis. These surveys include shoreline structures, population levels, bacterial levels, nutrients, runoff and other factors. A survey of the upper region of central Barnegat Bay, BB-2 (from Bay Shore to Sunrise Beach) by Kirwan (2005) showed that of the 13,500 acres (54.6 km^2), 65.6% were Approved, 8.0% were Seasonal, 15.1% Special Restricted and 11.3% Prohibited. A survey of the lower BB-2 area (Curtis 2004) indicated that this area had a total of 40,060 acres (162.1 km^2) of which 86.6% were Approved, 9.2% Seasonal, 2.5% Special Restricted and 0.9% Prohibited. The BB-3 survey was conducted in 2000 to 2004 (Curtis 2009), and showed that the shellfish growing area comprised 13,698 acres (55.4 km^2) of which 93.3% were Approved, 4.3% Seasonal, 1.4% Special Restricted and 1% Prohibited. Thus combining findings of the three surveys, in 2012 there were ~67,296 total acres of classified shellfish area in BB-LEH with 83.8% Approved, 8% Seasonal, 4.8% Special Restricted and 3.2% Prohibited. Examination of the clam distribution data and a visual comparison with the water classification areas suggests that there is little correlation between the abundance of clams and the areas in which harvest is restricted. This may indicate that the factors that are causing reduction in the clam population have little to do with harvest, or that harvest is taking place in unapproved areas, and we have no data to evaluate either factor. There is no available information to determine if closed areas have provided spawner sanctuary areas for adult clams within the estuary.

While the state monitors the areas for suitability for shellfish harvest, the monitoring data collected also indicate where pollutants are entering the system. In the past, New Jersey was a leader in reducing the areas that were unsuitable for shellfish harvest. While there are some localized pollution reduction studies, and monitoring to meet the National Sanitation Shellfish Program (NSSP) requirements, based on requests made through the state appointed Aquaculture

Advisory Committee to have someone provide it, there does not appear to be an overall plan designed to investigate the documented pollution in closed areas and to effect remediation. This leads to a loss of valuable recreational and commercial shellfish harvest.

In the past, clams harvested from Special Restricted waters were depurated at NJ depuration plants or subjected to relaying (transport and holding of clams in Approved Waters in the BB-LEH estuary). Depuration is a process by which filter-feeding shellfish are held in clean seawater (e.g. chlorinated, ozonated or otherwise disinfected seawater) in land-based systems, under conditions (e.g. temperature) that maximize their filtering activity, so that they purge their gastrointestinal tract of bacterial contaminants. Although this method is relatively effective in removing coliform bacteria, it is not very effective in eliminating viral contaminants (Lees et al. 2010). The hard clam relay program began in NJ in the early 1970s, and involved state-supervised harvest of clams from polluted waters and their transplant to lots leased by individual clammers in clean waters, where they were cleansed of bacterial contaminants for a minimum of 30 d (McCay, 1988). Over the years, relayers harvested clams from productive clam areas in the Manasquan River where recruitment rates at moderate to high density stations ranged from 3.0 to 31.1% (mean = 21.7%), and the Shark River, NJ, where recruitment rates ranged from 0 to 11.6% (mean = 4.8%) (McHugh 2001). Clams were also harvested from the Navesink and Shrewsbury Rivers, and Raritan and Sandy Hook Bays, NJ. From 1980 to 1984 the total NJ hard clam landings attributable to relays comprised 1.9% to 20.3% of the total state harvest (McHugh 2001). This relaying activity was completely discontinued in 2004 by the NJDEP Bureau of Shellfisheries due to multiple concerns. These included the potential risk of QPX introduction and low participation (M. Celestino, NJDEP, pers. communication). There were also concerns that enforcement was insufficient, and that participation was affected by changes implemented by the NJDEP Bureau of Marine Water Monitoring and Classification that allowed relaying only between May 1 and October and thus delayed the window of the clammers' profitability beyond the period of peak summer sales (W. Johnson, NJ Atlantic Coast Shellfisheries Council, pers. communication). Relay areas used in the past in western Barnegat Bay and Little Egg Harbor are shown in Figure 46 C & E respectively.

Conclusions:

- Based on water quality monitoring conducted by the NJDEP by sector, there are ~67,296 total acres of classified shellfish area in BB-LEH with 83.8% Approved year-round for shellfish growing. Restricted or prohibited areas are generally found along the shorelines and creeks.
- There have been no substantial changes in the percentages of classified waters over the last years (as reviewed by Curtis 2009).
- The presence of shellfish in uncertified and/or otherwise polluted areas leads to potential public health risk when these shellfish are illegally harvested either recreationally or commercially, especially in readily accessible nearshore waters. Remediation of water

quality should thus remain a high priority in the context of enhancement of hard clam stocks in the estuary and public health safety.

5.b. Anthropogenic Contaminants

Chung et al. 2007 reported that postlarval (200 to 350 µm) hard clams were one of the most sensitive species to a variety of contaminants. In 10 day-LC50 sediment exposure trials, the juvenile clams were more sensitive to fluoranthene (LC50 1.66 mg kg^{-1} dry weight) than normally used test animals (two amphipod species, two copepod species and grass shrimp). The small clams were 1.9 to 6.2 x more sensitive than juveniles of these other species and 1.9 to 1565 more sensitive than adults of the other species.

Fluoranthene is common in combustion products (boat exhausts). EPA guidelines for ERM (effects range median) and for ERL (effects range low) are 5.1 mg kg^{-1} and 0.6 mg kg^{-1} respectively, values well above and close to the sensitivity of these juvenile clams, and levels in some estuaries exceed the LC50 values for hard clams. Effect of other PAHs have not been tested, and data are not available to evaluate the importance of this in Barnegat Bay, but sediments in areas of high boat traffic should be tested. National Status and Trends indicates that fluoranthene is about 20% of the high molecular weight polycyclic aromatic hydrocarbon (HMWPAH) load in estuarine sediments. With this a guideline, it would take a reading of about 5,000 µg of HMWPAH g dry $weight^{-1}$ of sediment to yield mg kg^{-1}, and sediments in some sample locations in most of our major Atlantic harbors reach or exceed this threshold. In NY, areas in Long Island Sound, the New York Bight, the Hudson estuary and Raritan Bay, NJ, exceed this limit. The only site close to Barnegat Bay reported was in Great Bay which had 0.68 mg kg^{-1}, or about a factor of 4.5 below the ERL value for hard clams. (NS &T, 1991) In Barnegat Bay, areas of fine grained sediments with heavy boat traffic such as marinas may have sedimentary fluroanthene levels that approach those which are toxic to juvenile clams, but it is unlikely that large areas of the system are affected.

The BB-LEH estuary has experienced extensive bulkheading along its shoreline. Originally docks were built of cedar poles that were vulnerable to shipworms; these were replaced by creosoted wood which was subsequently removed from construction due to its potential toxicity to humans. The wood currently used is typically pressure-treated with chromate copper arsenate (CCA) which results in leaching of copper, chromium and arsenic. These compounds accumulate in fine-grained sediments and are toxic to many estuarine organisms (Weis and Weis 1996). Leachates were also found to cause avoidance of *Crassostrea virginica* larvae in laboratory assays (Prael et al. 2001). Leaching is a function of water flow conditions and age of the CCA wood, such that leaching of newly treated wood for a few months minimizes deleterious effects. Since the majority of new dock, pier and bulkheading work occurs in the spring, the presence of toxic leachates may coincide with clam spawning and the presence of larvae in the water column. The new material of choice is plastic lumber which is expected to have no deleterious effects on shellfish.

The susceptibility of hard clam eggs, embryos and larvae to various anthropogenic organic contaminants, such as petroleum products associated with oil spills, surfactants, and various pesticides (insecticides, pesticides, algicides and fungicides) was reviewed by Roegner and Mann 1991). These authors also reviewed the toxicity of heavy metals to *M. mercenaria* embryos, larvae juveniles and adults, and the accumulation and depuration rates of heavy metals by adult hard clams. The presence of heavy metals may interact with pH such that more acidic conditions will make the metals more biologically active. The mobilization of these metals may increase uptake and/or increase their toxicity. Moser and Bopp (2001) suggested that marinas may be a source of Pb in BB-LEH sediments as Pb levels in marina sediments were elevated compared to bay sediments. They found, however, that Pb concentrations were higher in older (from or before ~ 1972) than recent marina sediments, and suggested that this may be attributable to the decrease in the use of leaded gasoline in recent decades. Marina sediments were also found to be associated with higher Cu concentrations than bay sediments. The mean concentration of Pb in recent bay and marine sediments from BB-LEH (range = 42 – 116 $\mu g\ g^{-1}$) was higher than most other coastal lagoonal systems examined including MD and DE coastal bays (range = 7-34 $\mu g\ g^{-1}$), whereas Cu concentrations were comparable to those in other lagoonal estuaries (Moser and Bopp 2001). In general, these authors found higher levels of these contaminants, at levels that could potentially be toxic to biota, in sediments in the northern part of the BB-LEH estuary where there is a higher density of marinas, bulkheads and boat traffic.

<u>Conclusions</u>:

- There are insufficient data to assess the importance of anthropogenic contaminants to hard clams in the BB-LEH estuary. There may be areas such as marinas where these contaminants exceed tolerance levels.
- Boat traffic and human activity in the vicinity of docks and marinas is expected to pose the greatest threat of anthopogenic contaminants to hard clams, as levels may exceed tolerance levels at these sites.

6. Status of *M. mercenaria* populations in BB-LEH

6.a. Clam population abundance, distribution and size structure

6.a.i. Landings

Lower LEH was reported to contribute a high commercial yield of hard clams at least since 1929 and through the 1970s based on records obtained by Parsons Seafood, Tuckerton, NJ (Carriker 1961). These represent ~10% of the clams harvested from Little Egg Harbor (Carriker 1961, Fig. 20). Landings attained 7 million adults in 1929, and peaked at 16.7 million clams in 1946.The effects of variable fishing effort on these landings was not determined.

Consistent with the information provided by Carriker (1961), the BB-LEH ecosystem has experienced a major historical decline in landings of hard clams, as reflected in the decline in landings in Ocean County since 1960 (Fig. 21). Landings data, however, are typically under-reported and alone are often unreliable for stock assessment. In 1984 landings were estimated at \$4.8 million if corrected for under-reporting, yielding a dockside value to the state of \$6.7 million (Coastal Bay Clam Resources Task Force 1985, (see sec. 11). The Task Force also reported over 2300 commercial and 15,000 recreational licenses in the state of NJ.

Catch per unit effort data are more useful for this purpose, but such data are extremely limited in BB-LEH. Declining populations are also reflected in the reduction in the number of both recreational and commercial licenses issued for harvesting of clams (or all molluscs other than conchs since 2008) in NJ (Fig. 22). These data must be viewed with caution, however, as the purchase of licenses does not indicate to what extent they were used, and the decline in numbers may reflect other causes than the decline of clam populations, e.g., socio-economic factors, such as improvements in the economy leading to alternative employment. Other caveats in the interpretation of these data are given in the caption of Fig. 22. For example, commercial licenses once also included clammers working in relaying activities in Monmouth County that ceased in the early 2000s, yet traditionally most of the commercial licenses were sold to clammers in Ocean County and clam farmers from Ocean and Atlantic Counties, and relative changes would thus be at least representative of activity in the BB-LEH (G. Flimlin, pers. comm.).

Taking all the above factors into consideration, and based on the data shown in Figure 22, the number of recreational licenses was reduced by ~65% and that of commercial licenses by ~56% between 1980 and 2000, the period of greatest decline. This approximates the 68% drop in the Little Egg Harbor clam population between the mid 1980s and 2001. Over a 25 year period (1985 to 2010), there has been a loss of ~1,300 full and part time commercial clammers in NJ (Fig. 22). Over the same period of time, the number of recreational clamming license holders also dropped by ~10,000 (Fig. 22). Since the predominant hard clam area for recreational and commercial harvest had been the BB-LEH estuary complex, a very large portion of those lost jobs had been in Ocean County (G. Flimlin, pers. comm.). As a result of the decline in stocks and the development of clam aquaculture, some commercial clammers changed their focus to aquaculture. The recreational sector exerted more pressure on other common bay species like the blue crab. Presently clam aquaculture dominates shellfish production in the Atlantic County Coastal Bays of NJ (G. Flimlin, pers. comm.). In contrast to the BB-LEH estuary, waters of Sandy Hook and Raritan Bays remain excellent naturally productive hard clam areas (Kraeuter et al. 2009).

Hard clam populations have also experienced a dramatic decline in other Atlantic coastal lagoonal ecosystems, such as the South Shore Estuaries (SSE) on Long Island, NY (Fig. 24), and the inland MD bays (Chincoteague and Assawoman Bay, MD). Although the reciprocal decline in hard clam landings with increased regional human population growth shown in Fig. 21B is suggestive of overfishing as the cause of decline of hard clam populations in BB-LEH, evidence of cause-effect is lacking, and the role of other contributing factors remains unknown. In contrast, the precipitous decline of hard clams in SSE in the 1980s was clearly attributed to overfishing (Kraeuter et al. 2008), but continued decline of this population, despite markedly reduced fishing pressure in recent decades, has led to the hypothesis that other factors may be contributing to this decline. These factors include changes in the food supply that may lead to poor growth and compromised reproductive success of hard clams, poor fertilization success due to low clam densities, and/or a change in the abundance/composition of predators (Bricelj 2009). It has been speculated that a shift towards smaller phytoplankton [PP, $\leq$ 2-3 µm size fraction] may have occurred over past decades; yet, there is limited information on the phytoplankton species composition and size structure in these bays over appropriate time scales to substantiate this. While evidence is sparse, the available data suggest that growth has not changed appreciably in the SSE (sec.6.d.ii), and that at least some predator populations have not increased greatly (Polyakov et al. 2007).

Conclusions

- Landings of wild caught hard clams, and commercial and recreational clam licenses have all declined in BB-LEH. These appear to reflect a decline in the stocks (see below).

Aquaculture may be replacing some of the lost landings, but it too is struggling to survive in an area that is becoming increasingly urbanized. These factors clearly indicate that social connection with the clam resource within the Bay, a significant part of the regional ethos, is slowly being lost.

6.a.ii. Abundance Surveys

The only survey to encompass the entire BB-LEH system is that which was conducted in 1985-1986 by the NJDEP (Joseph, 1986, 1987). This survey used a small hydraulic clam dredge, with a knife edge of 1 ft and a box at the end lined with mesh that retained all clams >30 mm SL. The dredge was typically towed 100 feet from a marker buoy and two tows were made at each station. At stations where clay or shell substrate did not permit 100 ft tows, 50 ft tows were substituted. All live clams and paired valves (boxes) were measured to the nearest mm and graded into 4 size classes: seed (30-37 mm SL), littleneck (38-55 mm SL), cherrystone (56-76 mm SL) and chowder (>76 mm SL). Paired valves of dead clams were also recorded and their numbers were compared with the live individuals to estimate mortality at each station. Hard clam surveys were again conducted in 2001, but were limited to LEH, at 194 stations monitored from July 16 to August 31, 2001. A similar dredge and methodology was used for the LEH sampling in 2001 (Celestino 2003), with the major exception that only one dredge haul was made at each station. These two surveys, (Figs. 24 & 25) covered in BB, from Matoloking to Manahawkin, between May 22, 1985, and August 7, 1986 with 303 stations, LEH between July 28, 1986 and October 9, 1987 with 189 stations, and 104 stations in Great Bay between May 26 and November 1988. For purposes of abundance surveys recruitment is defined as the smallest size class collected (~30 – 37 mm). These animals would be mostly 3 year-olds.

In the mid 1980s (Joseph, 1986, 1987) hard clam populations were present at densities of (mean ± 95% confidence interval) 1.42 ± 0.18 (BB), 2.65 ± 0.44 (LEH) and 1.32 ± 0.47 m^{-2} (GB), respectively. A comparison of total clam densities (all size classes included) in the LEH survey in the mid 1980s vs. 2001 indicates that maximum abundances declined from 12.9 to 8.1 clams m^{-2}, and hard clams were absent from stations in western LEH (Fig. 25) (Celestino, 2003). Clam density in LEH had dropped to 0.974 ± 0.21 clams m^{-2}. The maximum density of chowder clams throughout the estuary in the 1980s was 12.89 clams m^{-2} (Fig. 26). In LEH chowder clams declined from 12.89 to 7.50 individuals m^{-2} in the mid-1980s to 7.59 m^{-2} in 2001 (Fig. 27). Chowder clams that were present at moderate densities in LEH during the mid-80s survey, were absent in shallower waters along both the western and eastern shorelines in the 2001 survey (Fig. 27). Sublegal clams, which attained a maximum density of 1.9 clams m^{-2} in LEH in the mid-1980s (Fig. 28) were present in only <5% of the total number of sites sampled in the 2001 survey. Where present, their density ranged from 0.13 to 0.48 clams m^{-2}. Additional surveys were conducted by the NJDEP in 2011 (LEH) and 2012 (BB) but these were not yet available for this report.

In 1964 Crawford and Allen issued a report on the abundance of shellfish from the base of Sandy Hook, to Cape May Canal, but concentrated on the Shrewsbury River to the Cape May Canal. The survey was not a resource sampling survey, but was limited to information provided by the NJ Division of Shellfisheries' field inspectors via records of densities on a chart. Hard clams were divided into 3 groupings, High, Moderate and Low:

High value - Areas producing an annual supply of hard clams capable of supporting a sustained commercial fishery.

Moderate value - Areas which produce commercial quantities of clams periodically but not on a sustained basis.

Low value - Consistent but poor clam production, not of a density sufficient for commercial clamming. Primarily of value for recreational clamming.

Hard clams were reported to occur in commercial abundance in about 58% of the waters. The upper end of Barnegat Bay near Toms River was classified as Low value except in deeper water where the resource was considered to be of moderate value. A small area on the Island Beach side was also classified as of moderate value. The remainder of Barnegat Bay was mostly of low value except near Barnegat Inlet and along the shore of Long Beach Island. Most of LEH from Brandt Beach through Beach Haven was classified as moderate. This zone ends with an area of high value off the cluster of islands containing Marshelder Island and extending toward the northern part of Parker Cove on the NE and toward Tuckerton on the SW. The Central and Western parts of LEH classified as of moderate value. The area around the mouth of the Mullica River and most of the NE side of Great Bay was deemed of High value with most of the remaining area on the SW side of Moderate value. Only the southern area near the inlet was of low value. These overall distributions generally mirror the areas of abundance today, but there is no way to quantify the number of clams.

In the 1960s Campbell (1965, 1966, 1968, 1969) surveyed the hard clam resources of Barnegat Bay off Forked River and Waretown in preparation for the construction of the Oyster Creek power plant. We have not been able to find any records of the station data so the information we have is based on contours on what appear to be copies of hand drawn isopleths of clam density on charts. The area surveyed was from ~2 miles north of Forked River south to Lochiel Creek and extended eastward toward Barnegat inlet and Clam Island. The stations were in a grid pattern running east and west along longitude and latitude lines at a 300 yard spacing. Samples were taken with a 16 ft, 12 tooth hand tong with baskets lined with ½” wire screen (the width of the basket was not reported). Two samples with these tongs covered approximately 5 ft^2 (sublegal clams were 15 to 46 mm in SL, littlenecks were 47 to 66 mm long and large >66 mm in SL. Contours were based on clams ft^{-2} (0.0, 0.1-0.5, 0.6-1.0 and 1.1-1.5).

In general, Campbell (1969) found moderate to low densities of hard clams throughout the area with the “large” size clams being the most abundant. Campbell averaged the numbers of clams from the 65, 66 and 68 surveys and found that the 7,306 acre area contained about 209,000 bushels. How the numbers were converted to bushels was not indicated. Few sublegal size clams were found, and most of these were at locations along the western shore from the mouth of Oyster Creek to Lochiel Creek at densities between 0.1 and 0.5 clams ft^{-2}. Littleneck-sized clams were more widely distributed than sublegal sized clams, and these were more uniformly distributed over the area from Oyster to Lochiel Creek than to the north of Oyster Creek. There were modest areas of littlenecks along the western shore from Oyster Creek north to Stouts Creek. The large sized clams were widely distributed throughout the area, but were more uniformly distributed in the area south of Oyster Creek. This distribution generally follows the broad area of medium sand outlined in Kennish and Olsson (1975). These distributions are similar to the NJDEP survey data for the same area in 1984 (Joseph 1986). Since the contour intervals of the early study are not the same as that used by the NJDEP it is difficult to determine if the overall density has changed, but there seems to be a general pattern of lower overall abundance. The 1984-85 survey (Joseph 1986) found densities ranging from 0 to 0.65 clams ft^2 compared with the range of 0 to about 1.5 ft^2 in the 1960s. To estimate the density of clams in the Campbell survey we have estimated the area within the contours that combine the 65, 66 and 68 surveys (Campbell, 1969), the 7,306 acre area and the average density for his contour categories (0, 0.1-0.5, 0.6-1.0 and 1.1-1.5 = 0. 0.3, 0.8 and 1.3 clams ft^{-2}) to estimate the numbers of clams in the area (77,826,468). To compare the 1984 population with the Campbell data we selected stations from the NJDEP sampling grid that were in the area depicted by Campbell, and obtained an average clam density (0.186 clams ft^{-2}) and multiplied this by the 7,306 acres and the conversion of 43,500 ft per acre to obtain an estimate of the 1984 density (59,127,783 clams). The 95% confidence limits on the 1984 data yield a range in abundance of 74,367,774 to 43,761,621 clams. This suggests that there may have been a slight drop in the overall abundance between the two surveys, but given that the estimates we derived from Campbell's data are not very accurate we conclude that there was no significant change in the 17 to 18 years between these two surveys, and in general the areas of high clam density remained in approximately the same areas during the 17-18 year period. This lack of change does not mean that the population remained static for all those years. Kennish et al. (1984) reported that clam populations in central Barnegat Bay had declined 80% between the Campbell survey (1965) and 1978/79 when Vouglitois & Kennish (1976) surveyed the same area. How this estimate was compared to the Campbell data was not explained. Unfortunately, the data from this survey (depicted in Fig. 3 in Kennish et al. 1984) do not appear to have survived (M. Kennish, Rutgers University, personal communication).

Conclusions:

- Clam populations appear to have decreased since the 1960s, but the only area where a change can be quantified is LEH. The lack of monitoring data at the appropriate temporal and spatial scales makes scientific assessment of clam population changes impossible.

6.a.iii. Other population data

In the mid to early 1960s a "survey" of bivalve resources was made by the US Fish and Wildlife Service in conjunction with a proposed Intracoastal Waterway improvement project. The FWS relied on information provided by NJ DEP, Division of Shellfisheries and constructed a series of maps delineating the resources within the area south of Raritan/Sandy Hook Bay to Cape May. The hard clam resources were classified into 3 groups: High Commercial Value, Moderate Commercial Value and Recreational Value and placed on 5 Coast and Geodetic survey Charts (No. 824 to 827). The third chart (825) contains all of Barnegat Bay and most of Little Egg Harbor Bay. The fourth chart contains the remainder of Little Egg Harbor Bay from a line that connects Tuckerton Point to a point just south of the town of Beach Haven.

Clam distribution on these charts mirrors that on later charts in that clams are reported to be scarce or non-existent north of a line that connects Lanoka Harbor to a point on Island Beach. From that area south the shallower portions of the bay, with the exception of a band that runs along the western shore have recreational levels of clams and the deeper parts commercial quantities. This pattern continues south to Gulf Point on the western shore. From Gulf Point southward the entire inshore area is classified as recreational and the eastern side of the bay is of moderate commercial value. The only area of high commercial value is the area near the island inside of Little Egg inlet. How these general patterns relate to the quantitative surveys of the 1980s and 1990s in terms of absolute abundance is not known, but the overall pattern of distribution remains approximately the same.

The NJDEP also conducts surveys in response to applications for shellfish lease grounds (Appendix I, sec. 10) and shoreline development (Appendix II). The methods for these areas varied according to the site, but typically tongs, rakes or grab sampling or combinations of these methods were utilized. The number of samples also varied, but typically at least 10 tong or rake samples and 3 grab samples were taken per site. Live clams and boxes were enumerated and both were usually measured. All grab samples were sieved to estimate seed clams. Rakes were one of three: 2.33, 1.97 and 1.79 feet wide and were typically dragged for 25 to 50 ft for each sample. All tow lengths were recorded. Tongs were 18.5" wide with 6" tines and sampled 3.08 ft^2. All data on numbers of clams were converted from the rake size and tow length, tong width and opening, and grab sample to 1 ft^2. The numbers of clams per unit area were then averaged to obtain the number of clams per unit area at the site. These data indicate that clams occupy many of the shallow areas within the bays, but because the samples are limited in spatial and temporal extent with one exception, they do not provide sufficient information on which to base any conclusions about the resource. The exception is a recent survey for a number of leases in the Middle Island area conducted in 2008 (see sec. 10).

The size structure of hard clam populations, as measured by the relative contribution of sublegal and commercial size classes (littlenecks, cherrystones and chowders) differed considerably between BB-LEH and Great Bay during the 1980s survey (Fig. 29). Cherrystone clams dominated the population in BB with 71% and chowders comprised 17.3%. Cherrystone and chowder-sized clams contributed 50 and 37%, respectively to the LEH population. The latter bay somewhat mirrored the Great Bay population of 51% chowders and 26% littlenecks. The high percentage of cherrystone clams in Barnegat Bay may be due to poorer conditions for clams in that bay, but there was no evidence of a difference in size structure between northern and southern BB despite the salinity differences experienced between these two zones (Fig. 30). The size structure of clam populations changed in LEH between the mid-80s and 2001 surveys: the relative contribution of sublegal-size clams declined from 3.9 to 1.7%, and that of chowder clams increased from ~50 to 60% (Fig. 31). These changes are reflected in the population changes in which the number m^{-2} fell from 2.57 to 0.94 and the seed (the SL class) went from 3.5% of the population to 1.5% and experienced the largest decline of any size class (85.6%) (Table 5). There was also an increase in the % of stations surveyed in LEH which had 0 clams, from 3.1% in the mid-80s survey to 35% in the 2001 survey. Although absolute abundance data may be affected by differential sampling gear efficiency for the different clam size classes, changes in relative abundance over the two surveys remain valid.

<u>Conclusions:</u>

- These trends provide evidence for historically poor and possibly declining recruitment and a declining population over time in LEH. Whether the LEH situation reflects the entire Barnegat Bay system is unknown, but anecdotal reports indicate substantial drops in the numbers of clams in Barnegat Bay as well.

6.b. Reproduction and larval ecology

Mercenaria mercenaria are characterized by separate sexes, attain first sexual maturity at ~2 yrs (~30-35 mm SL) in mid-Atlantic estuaries, and have planktotrophic larvae. Limited information is available on reproduction and larval ecology of *M. mercenaria* in the BB-LEH estuary per se. An early comprehensive field study was conducted in the summer over four years (1947 to 1951) in LEH (Carriker 1961). This bay is characterized by relatively uniform vertical and horizontal salinities and moderate exchange that favored the high retention of larvae to setting within the system This homogeneity in salinity and temperature (vertical range during the summer typically ≤ 0.5 and $\leq 1.4^{o}$C, respectively) was attributed to the relatively small volume of freshwater that enters the bay (via creeks which transport limited freshwater except during heavy rainfall) and the rapid mixing of the water column resulting from the complex tidal circulation and wind action within a shallow basin [generally 1-2 ft (0.3 to 0.6 m) at mean low water except for a few deeper channels]. Higher retention of clam larvae in the central basin of Lower LEH than on the eastern side of the bay was related to the relatively shorter tidal extension in the former.

In Carriker's (1961) study the timing and duration of the reproductive period of hard clams in LEH was determined based on a) the capacity to induce spawning of adults collected from this bay in the laboratory, and b) from the presence and abundance of veliger larvae in the water column in the field (Fig. 32). The minimum duration of the planktonic veliger stage of clam larvae observed in LEH was 7-8 d (at a median daily temperature of 23.4 to 26.2^{o}C and mean daily salinity of 30.4 to 31.4). This is supported by laboratory observations. In the Lower LEH hard clam spawning typically started in late June (20 to 24) and peaked in July, and evidence of some spawning continued into late August and the first week of September. Laboratory induction of spawning was achieved throughout July but was not successful from clams collected in August. The mean amplitude of all tides during which spawning occurred was 1.78 ft [range = 1.25 to 2.56 ft (0.38 to 0.78 m)], and the frequency of spawning was maximal within the range 1.6 to 1.9 ft (0.49 to 0.58 m).

Spawning during the summer was strongly influenced by both temperature and tidal height (Carriker 1961). Most spawning events (73%) occurred during a period of rising median daily water temperature, while they less commonly coincided with falling median daily temperature, averaging 26.2 and 24.4^{o}C respectively. The overall mean median spawning temperature was 25.7^{o}C (range = 22 to 30^{o}C). Maximum spawning likely occurred close to the ebb slack tidal period when maximum water temperatures prevailed, and both maximum spawning frequency and larval densities were observed during neap tides, thus contributing to high larval retention. Maximum densities of clam larvae occurring in July varied greatly among years (Fig. 32), presumably due to differences in the temperature regime, ranging from 2,780 to 67,200 100 L^{-1} and was highly patchy horizontally. Densities were maximal in central LEH and declined progressively toward Manahawkin Bay, Tuckerton Creek and Little Egg Inlet. Complete loss of larvae from the water column coincided with mean daily tidal amplitudes > 2.1 ft (0.63 m; i.e., tidal exchanges > 37%). Within creeks maximum densities of veliger larvae remained near the surface during daylight hrs and coinciding with maximal current velocities during late flood and early ebb tides, and decreased to mid-depth as currents decelerated. In central LEH maximum larval densities occurred at mid-depth regardless of the stage of the tide (perhaps due to reduced turbulence), but were also absent near the bottom during daylight hrs. During darkness veligers generally showed a broader vertical distribution, but maximum densities were never observed near-bottom. These data suggested that the larvae were phototactic and exerted some degree of control over their vertical distribution. In contrast, older larvae (umboned stages) were more or less uniformly distributed throughout the tidal cycle. The fact that veliger larvae generally remained away from the bottom was suggested to reduce the risk of benthic predation. Periods of minimal precipitation resulting in reduced flushing also favored the presence of clam larvae within the bay. The effects of precipitation on spawning of adults was not determined. When the appearance of larvae in the water column coincided with periods of limited precipitation and medium to low tidal amplitudes, and thus minimum flushing and exchange, recovery rates from the first-feeding D-stage larva to the setting stage were estimated at 2.6%.

Setting of clam larvae did not coincide spatially with the distribution of adults. This is at odds with the laboratory information in Keck et al. (1974) who found that setting larvae were attracted to sediment treated with fluids from the adult mantle cavity. In the field study, maximum setting (plantigrade or immediately post-metamorphic) stages were found attached byssally on hard substrate such as oyster shells, and in the absence of such hard structures, on sand grains. These field studies indicated that post-settlement stages occurred in sediments ranging from clean sand to organic detritus.

Hard clams have typically been considered opportunistic bivalves that reproduce primarily at the expense of the phytoplankton they feed upon during the spring when they undergo gametogenesis (Ansell and Loosmore 1963). However, multi-year studies of both native and transplanted clams into central Great South Bay, NY, by The Nature Conservancy found that reserves accumulated in the fall, reflected in the condition [defined as (dry tissue weight x 100)/internal shell cavity capacity) of adult hard clams the previous fall was critical to the success of reproduction the following summer (Doall et al. 2008, LoBue 2010). Thus, the condition at the end of the fall explained ~89% of the variance in spring condition. This is consistent with the results from a model simulating population dynamics of this population (Hofmann et al. 2006).

Highly variable site-specific reproductive output of hard clams among bays was found both by Newell et al. (2009) and LoBue (2010). A 1-yr study found that that the reproductive output of hard clams varied significantly among south shore Long Island, NY, bays, and was generally lower in these than in Sandy Hook Bay, NJ (3-fold maximum difference among sites; Newell et al. 2009). Large inter-annual variability in reproductive potential, as measured by the condition index of adults in NY bays was also documented by LoBue et al. (2009). The onset of temperatures > 10^{o}C in the spring, and < 10^{o}C the previous fall were found to affect adult condition. In both studies lower reproductive performance was related to the dominance of small (< 5 µm) microalgae as a percent of total microalgal biomass in the water column.

<u>Conclusions</u>:

- No information is available on the reproductive output of hard clams in BB-LEH.
- Early data from the 1940s showed that Little Egg Harbor was once a system that favored hard clam spawning, and larval retention, growth and survival. No relevant information is available on larval distributions and performance since that time.
- The food supply (phytoplankton composition), particularly in the fall, is an important factor determining the condition index attained by reproductive adult hard clams.

6.c. Recruitment

While there is relatively little information on recruitment of hard clams in New Jersey and in the BB-LEH in particular, three studies have provided some general information. Connell (1983) followed a set of clams on a bar in Shark River which empties into the Atlantic Ocean north of Barnegat Bay near Belmar, NJ, from October 1979 to October 1980, with monthly sampling (Fig. 33). In this survey he used a 1.5 mm sieve under a 6 mm sieve, and the smaller size was defined as recruits. Each month 10 shovel fulls (approximately 0.5 m of sediment) were removed for each sample and 5 replicate samples were collected. He found an initial population of ~840 m^{-2}, but the density was reduced to 376 by December, to 194 by January 1980 and to 30 by June of the following year (~3.6 % survival). These clams must have set relatively late because the average size was < 5 mm and remained at this size through the winter/early spring (Fig. 34). These are the only data on juvenile hard clams from a natural population in NJ, and must have represented a relatively good set because there are so few records of significant densities of hard clams <10 mm in the State. Connell (1983) attempted to determine the cause of the winter mortality by comparing the weight of shell material in two categories: shell hash and valves. This analysis generally showed that except for the January 1980 sample, when valves made up 20% of the weight, shell hash was always > 90% of the total. The losses were presumed to be due to crab predation on the smaller seed, and in the winter black ducks were thought to cause significant losses.

Connell (1983) also developed a life table (Table 8) for hard clams in Shark River. The area had been closed to harvest for many years due to pollution. He based the year one and two data on his analysis of the recruitment data (Fig. 35) and then extrapolated the information based on a cohort of 10,000. By the end of year 1 only 58 clams were left. His life table analysis does not show the large mortality in the years that Kennish (1978) reported for the Barnegat Bay population (years 5-6 - see below for more information). A size analysis of the population in Shark River showed that there were very few clams in the 30 to 65 mm shell length classes. Based on the life history table Connell (1983) surmised that the hard clam population should be about 28 clams m^{-2}. It is not apparent how Connell made this analysis since clams 30 mm SL are at least 3 years old and those 65 mm could be age 5+. Since harvest was not a factor, Connell (1983) attributed the lower existing population levels (8.6 clams m^{-2}) to recruitment failure. If the theoretical analysis of Connell (1983) is compared with the data from Kennish (1978) (Table 8 and Fig. 35), and the assumption is made that mortality rates in Shark River increased at the same age as in Barnegat Bay (approximating clams in the 45 to 65 mm size range) then there would be no need to call on recruitment failure to account for the discrepancy. Kraeuter et al. (2009) working in Raritan/Sandy Hook Bay system also noted an increase in mortality of clams in these intermediate size classes, but their reported losses were not of the magnitude described by Kennish (1978).

A study in Absecon Bay, an estuary located south of Great Bay (Durand and Gabry, 1984) provides some additional general information on hard clam recruitment in NJ. In this study, clam recruitment (based on animals collected on a 1 mm sieve) can be evaluated by data from 25 Peterson grab samples taken quarterly (March, June, August and November) at 3 sites (reference, spoil and channel) from August 1977 to August 1982 (Fig. 36). The grab removed 0.06 m^2 and all material was sieved on a 1 mm screen. All clams <1 cm were considered to be recruits. Analysis of these data indicates no differences between the collection areas (one way

ANOVA, p = 0.19). The combined data yield an overall annual recruitment rate of about 1 m^{-2} for the period. There was substantial variation in this recruitment pattern on a quarterly basis (Fig. 36A). If the data are combined so that 4 quarters of the year (J A N M for 1978 to 1981, A N M for 1979 and J and A for 1982) are used to indicate average annual recruitment (Fig. 36B), then the years with 4 months of data ranged from 0.7 to 3.8 clams m^{-2} while the other two incomplete years showed lower rates. These data are generally in agreement with other estimates of hard clam recruitment. The only estimate of recruitment for Barnegat Bay was between 0 and 0.5 clams m^{-2} yr^{-1} reported for experimental plots established between 1990 and 2000 (Kraeuter et al. 2003). A range of 0.1 to 1.06 one year-old clams m^{-2} yr^{-1} was reported based on 26 years of data from Great South Bay, NY (Kraeuter et al. 2005), and Kraeuter et al. (2009) estimated a recruitment rate of 0.6 to 0.7 clams m^{-2} in Raritan Bay, NJ. Thus the recruitment rate observed by Connell (1983) in Shark River is at the very high end of the range, and those reported by Kraeuter et al. (1997) are more in line with the low recruitment for BB and LEH suggested by Kennish (1978) and Campbell's 1960s data.

Based on a spawner/recruit analysis of the long term annual survey data (1970s to the 2000s) of the hard clam population in Islip waters of Great South Bay, NY (Kraeuter et al. 2008) suggested that a bay wide density of ~0.7 clams m^{-2} (= 0.065 clams ft^{-2}) was the minimum necessary to sustain the population (Fig. 37A), and the optimum was around 5.0 clams m^{-2}. Planting numerous scattered plots of adult clams at the 5 m^{-2} density throughout an area that had and extremely low resident population appears to have been an effective "spawner sanctuary" method (LoBue, 2010). This relationship was subsequently incorporated into a population dynamic model for that system (Hofmann et al. 2006), and this model has been modified to evaluate the effects of brown tide on hard clams in Barnegat Bay (unpublished data). Recruitment limitation was also suggested as a potential cause of the decline of hard clam populations in GSB (Islip Town waters), given that the number of recruits per adult (adults defined as clams > 2 yrs old) fluctuated around a time-averaged value of ~ 0.14 between 1979 and 1995 but consistently remained below this mean between 1995 and 2003, during a period of recurring brown tide (Fig. 37B).

It is not possible to generate a spawner/recruit analysis for BB-LEH because the data are not available and the smallest size classes collected do not encompass the 0- or 1 year-class animals. To derive an estimate of recruitment relative to the adults present we have used the sublegal numbers from NJDEP data, and compared them to the total of the other size classes (i.e. reproductive adults). This approach has two major difficulties. The sublegal class is at least 2 years old and probably 3, and we have no estimate of the abundance of any animals two or three years earlier. In addition, the sublegal class almost certainly contains more than one year class. With those major caveats we computed the number of sublegal clams per adult for BB (0.035), LEH in the 80s (0.017) and LEH in 2001 (0.015). For comparison we also computed the same index for GB in the 80s (0.081) and the combined Raritan and Sandy Hook Bay (R-SH) index for 2000 (0.125). All these data were collected by NJDEP and by very similar methods so the indices are comparable.

In comparison, recruitment of age 1 clams in Great South Bay, NY, relative to the adults, ranged from 0.05 to 0.35 seed/adult for the period 1979 to 2003 (Kraeuter et al. 2008). These values ranged from 0.1 to nearly 0.35 from 1979 to 1996, and then dropped to the range of 0.05 to 0.09 from 1996 to 2003. The cause of this significant nearly decadal long decline is still not completely understood.

The only data that allow comparisons are for LEH between the 1980s and the 2001 survey when the number of clams dropped by about 67%. In contrast the sublegal size clams dropped by about 84%, but the sublegal/adult ratio dropped by only about 56%. The latter figure indicates that while recruitment, as measured by the number of sublegal clams, is substantially reduced, the number of seed per adult has not diminished as much. This metric, when combined with the increased area in the western portion of the bay with no or very few clams suggests that processes affecting larger clams may be as important as recruitment issues in explaining the large drop in abundance.

Conclusions:

- Hard clams generally recruit at very low rates. These rates are typically in the range 0.1 1.0 clams m^{-2}. For a long-lived species such as *M. mercenaria*, important, population-sustaining recruitment events may be episodic and thus data from any one year can mask long-term recruitment trends.
- The BB and LEH numbers of sublegal clams/adult are low relative to GB and very low relative to the same index for the Raritan/Sandy Hook bay system where the clam population appears to be doing well.
- The densities of hard clams reported during the 2001 survey were $\leq$ 0.8 clams m^{-2} ($\leq$ 0.074 clams ft^{-2}) over a large portion of LEH (Fig. 25), and thus below the density threshold that was suggested to be required for the maintenance of self-sustaining population in GSB, NY (Fig. 37). Based on the spawner-recruit relationship derived for GSB, NY, clam population densities determined during the 2001 survey in BB-LEH are insufficient to support a robust, sustainable wild fishery.
- A recent NJDEP survey conducted in LEH in 2011, and in BB in 2012 (results are not included in this report) will provide updated information on bay-wide hard clam densities. Based on earlier surveys, it is thus likely that hard clam populations in BB-LEH are recruitment limited.
- If the system is recruitment limited due to low population density, then establishing and maintaining multiple areas of moderate (~5 m^{-2}) densities that can potentially ensure fertilization success will likely enhance overall recruitment.
- There was a substantial decrease in total clam densities in LEH from the 1980s to 2001, but the number of recruits per adult has not declined at the same rate. This suggests that while part of the lower overall recruitment on a m^{-2} basis can be attribute to fewer adults to produce the recruits, processes acting on larger animals may also be important and should be investigated.

6.d. Growth

6.d.i. Settlement to Age 1

The same reasons that make studying recruitment to hard clam populations difficult also makes obtaining growth data from the field a challenge: few seed are typically found and predation rates are high. Connell (1983) reported the size of clams in October to be 5.34 mm SL. This suggests that while this was an abundant set, it must have been a relatively late set. By November of the following year the clams had reached 15.27 mm SL suggesting that growth during the second year at this site was typical of what is expected in NJ waters (Fig. 34). If the clams had been in the normal 8 to 15 mm SL range by the end of year 1 then they probably would have approximated the 20 to 30 mm size by the end of the second growing season.

Under land-based culture conditions, juvenile clams (3 size groups from 4.5 to 12 mm initial SL) were deployed in upwellers from May 13 to August 23 in 2005 and from May 24 until September 13 in 2006 at a hatchery in Tuckerton, NJ (Kraeuter and Bricelj, unpublished data). Clams were replaced with new individuals after a 3 to 4 week growth period. Weekly salinities during the 2005 and 2006 study periods averaged 27.6 (range = 25.8 to 31), and 28.8 (range = 25 to 31), respectively. Growth of juvenile clams during May 2005 was reduced due to low temperatures, and began to decline in the last weeks of the 2006 experimental period (Fig. 38). Mean weekly growth rates ranged from 0.4 (57 µm d^{-1}) to a maximum of 1.5 mm (214 µm d^{-1}). Average weekly growth excluding the first 2 wks in 2005 was 1.02 mm wk^{-1} (145 µm d^{-1}) and in 2006 it was a nearly identical at 1.01 mm wk^{-1}. These results mirror those anecdotally reported by aquaculturists in NJ.

Maximum growth of juvenile *M. mercenaria* (3 to 15.4 mm SL) determined in the field (NY waters and thus relevant to NJ) was reported at ~ 1.05 mm wk^{-1}, and under optimum cultured food and temperature conditions (20-21^{o}C, size range = 6 to 31 mm SL) it ranged between 83 and 96 µm day^{-1} (reviewed by Malouf and Bricelj 1989 and Grizzle et al. 2001). We are not aware of published data on in situ juvenile growth rates for *M. mercenaria* juveniles in the BB-LEH estuary in relation to environmental parameters, although these data are currently being generated at four sites along this estuary via an ongoing (2012) research project supported by the NJDEP.

Conclusions:

- Growth rates of juvenile clams can be greatly affected by temperature, food supply harmful algal blooms and other short term events. There is evidence that compensatory growth can occur.
- There is no direct field measurement of growth in BB-LEH. Information from a clam hatchery using water from Little Egg Harbor for seed production suggests that juvenile growth is similar to that in other mid-Atlantic systems, although interannual, seasonal and site-specific variability is expected to be high and remains unquantified.

6.d.ii. Adult growth rates

Information on growth of clams obtained by field population surveys may be affected by selective removal of small individuals by predators and large individuals by harvesters. Typically clams reach 10-15 mm by the end of the first summer in mid-Atlantic estuaries, and depending on the timing of setting this is consistent with the ~1 mm growth per week reported in hatchery studies.

Average growth can be obtained from size-at-age analysis, where age is determined from shell sections. Growth curves for *M. mercenaria* in NJ estuaries are shown in Figure 39 and compared to those obtained in Great South Bay, NY (Buckner 1984 and Laetz 2002). Kennish (1978) and Kennish and Loveland (1980) examined the size distributions of live and dead hard clams in the vicinity of the Oyster Creek Generating Plant, fitted various growth models

(Gompertz, logistic, and monomolecular) to the hard clam data and concluded that all three were adequate, but that the Gompertz equation provided the best fit (R^2 = 0.982).

No attempt was made to evaluate the von Bertalanffy equation. In addition, Kennish (1978), based on shell microstructural analysis found that the clams in the area had very regular growth characteristics. "Only a few specimens per sample need be analyzed microscopically to obtain the overall growth plan of the species at that site." In addition, Kennish (1978) reported that no detectable growth effects could be attributed to the plant operations. He also reported that recruitment had been poor for many years and except for one site Kennish (1978) could not find evidence of recruitment either in the live or dead assemblages from 1973 to 1976. Growth was rapid for the first 3 to 4 years (Fig. 39) and mortality was low. After the 4th year growth was reduced and by ages 5-6 mortality rates began to increase so that most of a cohort was lost by age 9. Growth (size at age) was similar to that in Great South Bay, NY, as described by Buckner (1984) (Fig. 39). This implies that at least a proportion of each cohort will reach market size by age 3 and almost all will reach market size by age 4.

Haskin (1949) compared the growth of clams (initial wet weight vs. final weight in g) at four sites in New Jersey: Delaware Bay at the Cape Shore, Jarvis Sound, Surf City and Raritan Bay. Growth was measured on plantings of all sizes available and data were averaged. The best growth was at Cape Shore in 1947 (reaching 100 g in 4 years) while in 1948 at the same location it would have taken an additional year to reach the 100 g size. Clams in Raritan Bay performed the worst and leveled off at about 60 g. Those in Surf City, the only location in the BB-LEH system, required 6 years to reach the 100 g mark.

Durand and Gabry (1984) also estimated growth in wet weight of clams at their reference and spoil site. We applied a conversion from wet weight (WW) to length [SL (cm) = 1.4733 x $\sqrt[3]{WW}$] from Haskin (1949) to the Durand and Gabry (1984) data (Fig. 40). These data generally conform to a standard growth scenario for this species with little or no growth in the winter months.

Grizzle and Morin (1989) placed individually numbered clams 30 to 44.6 mm SL in various types of sediments in Great Sound, NJ. Growth was measured after 15 weeks in the field and growth was between 9.5 and 11.5 mm SL or a rate of 0.63 to 0.76 mm per week. This study attributed differences in growth at various sites to the horizontal flux of particulate organic matter and showed that growth was not affected by sediment type.

Kraeuter et al. (2003) provide size-at-age data for clams from the Gulf Point area of LEH based on shell sections. Growth was relatively rapid during the first 4 years when the clams reached about 55 mm SL (12-14 mm yr^{-1}), and then dropped to about half that rate for the remaining years. In Raritan Bay, Kraeuter et al. (2009) found that growth based on size-at-age shell sections was slightly less than that based on growth of measured individuals. The growth curves were similar, but that of the size-at-age data began at age 0 with 0 size, whereas those of the measured animals began with about an 11 mm size at age 0. This separation persisted throughout the growth period. Thus for the size at age data the clams would reach littleneck size at age 4 to 5, but based on the growth data the clams reach littleneck size at age 3 to 4. These rates are slightly less than the LEH growth rates (9.6 to 11.6 mm yr^{-1} for the first 5 years), suggesting that rates are slightly lower in Raritan Bay, as Haskin (1949) had found, but the differences could simply be due to differences in the techniques being used.

The height measurement in Buckner (1984) is at a different orientation that that illustrated by Kennish and Loveland (1980), so converting from height to length using the equation of Buckner (1984) (L = 1.4828 +1.081H) introduces a systematic error that would reflect any differences between the orientation of the measurements. Unfortunately, Kennish and Loveland (1980) do not provide a conversion equation, and simply plotting heights for comparison would introduce the same bias, such that comparisons with other studies would also be biased. Thus the growth curves (size-at-age) depicted in Figure 39 should be viewed with some caution. In general, however, the growth rates in Great South Bay and Barnegat Bay are very similar, and comparison of the growth in Buckner (1984) with the more recent analysis by Laetz (2002) from the same location did not show any significant differences. Kraeuter et al. (2003) provide size at age data for a hard clam population in the area off Gulf Point in LEH. The laboratory analysis of the ages of the clams reported in this study was conducted by Kennish, and shows a lower growth rate after year 4 than that found by Kennish and Loveland (1980). It is noteworthy, however, that the Kraeuter et al. (2003) data were from many fewer specimens (111 vs. 277) and thus may reflect sampling error, site or fishing pressure differences, or a real decline in growth, but it is impossible to establish this from these limited studies. In any case, the growth during the first 4 years is virtually identical for the four studies depicted.

Conclusions

All the above growth data (Haskin 1949, Kennish 1978, Durand and Gabry 1984, and Kraeuter et. al. 2003) are consistent with data from other areas in the mid-Atlantic and the experiences of aquaculture growers in the region (e.g. reviewed by Grizzle et al. 2001).

- Hard clams reach about 8-12 mm SL by the first winter, 20-25 mm by their second winter, and 35 to 40 mm by the third. A portion of the population is thus marketable as littleneck by age 3 and the bulk of the population will reach that size by age 4. These approximations are for areas in which good growth is expected.
- There is little data on which to base growth under poor conditions, but it is likely that it will be at the lower end of the ranges given above. Growth in these poor areas, however, will probably begin to decline more rapidly as the animal reaches age 4 than in areas characterized by good growth.

6.d.iii. Lifespan and mortality

The maximum recorded lifespan of *M. mercenaria* was estimated at 46 years (Peterson and Fegley 1986). A recent estimate of 106 yrs and maximum SL of ~ 120 mm were obtained based on analysis of sectioned shells from live specimens collected from Buzzards Bay, MA (Ridgeway et al. 2011). The largest hard clam reported to date (135 mm SL) was found offshore, off the Cape May Inlet, NJ (Kraeuter, unpubl. data). However, examination of dead assemblages of clams from NJ waters showed that most clams lived < 9 yrs (Kennish 1980). In general populations experiencing limited or no harvest will have greater proportions of large clams than those that are harvested frequently (Fegley 2001). The two studies (Connell 1983, and Kennish, 1980) that have assessed survivorship in New Jersey waters, yield approximately the same end point by age 7, but the structure of the populations was substantially different (Fig. 35). The Connell (1983) data were based on a life table generated from direct measurements obtained from Oct. 1979 to Jan. 1981. The data from Kennish (1980) represent data collected from life tables based on size-at-age and mortality from shells collected from Barnegat Bay and sectioned. The main difference is the large reduction in numbers in the Connell data (based on field measurements) in the first two years. The author's monthly measurements suggest a decline from an initial cohort of 1000 in October to 238 one month later and 7 by the end of the first year of life. This is further reduced to 1.5 by the second year. In both cases the data suggest a relatively short lifespan in shallow New Jersey waters.

In addition to data on live animals, the NJDEP also recorded the numbers of boxes (dead clams with both valves attached) as an estimate of mortality. While the length of time valves remain attached to each other has been examined for oysters, it has never been evaluated for hard clams. As with oysters, it is likely that this will vary with size and temperature, but with clams it may also vary with sediment type. Valves may remain attached to each other longer in sticky muds than in less cohesive sediments. Malinowski (1993) gave mortality data for adult (>35 mm SL) hard clams in Rhode Island. He estimated that mortality ranged from 0.5 to 8.5% with an average of about 4.1%. Of the 354 clams that were planted, 324 were found alive and 14 were dead, leaving 16 clams unaccounted for. Kraeuter et al. (2009) compared size-specific mortality rates (25 mm to >65 mm) for marked clams planted in intertidal plots in Raritan Bay, NJ, with the NJDEP box counts from the same system. The experimental method yielded differential mortality based on size, but overall the rate, based on animals recovered as boxes, was about 2%. This probably underestimates the natural rate because significant numbers of animals were not recovered from the plots and thus could not be assigned to either the live or dead categories. NJDEP box count mortality for this population was about 8%. It is likely that the experimental estimate is too low, because some of the missing clams were found as shell outside the experimental area. It is also likely that some boxes last longer than 1 year and thus the box count estimate of mortality is too high. This apparently small difference is important because of the typically low recruitment rates of hard clams. The extent to which box counts quantify hard clam mortalities is thus uncertain, but until another method is developed it is the only practical method of assessing relative mortality.

Box count mortality in Barnegat Bay (1985-1986) was about 12% and in LEH (1986-1987) it was about 9.6%. By 2001 the box count mortality in LEH had risen to 40% and the number of stations with no clams had increased from 2.6% to 21.1%. The percent of stations with all dead clams in LEH was 0.05% in the 1980s while in 2001 it was 19.1%, and the percentage of stations with 0 mortality remained about the same (13.8% and 13.0% for the 86-87 and the 01 time periods, respectively). The high mortality rate depicted by Kennish (1978) for clams that are <7 years old is relatively unusual for an animal that has a total life expectancy of 50+ years. The high rate is however consistent with the large numbers found dead in the NJDEP survey. Assessment of mortalities in BB-LEH is one area where a targeted study should be focused.

Conclusions

- The increase in the estimated mortality between the surveys conducted in the 1980s and 2001 suggests that, in addition to lower recruitment, an increased mortality rate is also reducing the population in BB-LEH, and that it may be a significant part of the reduced recruitment. The cause/s of the additional adult mortality remain unknown and additional studies on this aspect are warranted. Although the time that paired valves remain attached has not been determined and is likely to vary with sediment type, thus affecting absolute rates of mortality, it should not affect relative comparisons between surveys that used comparable sampling methods.

7. Pathogens and disease

Unlike oysters, *Crassostrea virginica*, hard clams are subject to few diseases. The protistan parasite QPX (Labyrinthomorpha, Thraustochytriales) is the main known source of disease-related mortalities in *Mercenaria mercenaria* along the northeast coast (Ford 2001). This disease has been found in aquaculture plots in Jenney's Creek (Great Bay) near the 7 Bridges Road causeway (Ford et al. 2002). QPX has also been found in aquaculture populations in Dry Bay, near Tuckerton, and in wild clams in Raritan Bay (Ford et al. 2002). It is known that some aquaculture strains, typically those derived from southern stocks are more susceptible to this disease than NJ or MA aquaculture stocks (Ragone-Calvo et al. 2007; Kraeuter et al. 2011). While this disease is obviously present in the BB-LEH system, evidence to date suggests that it is not a significant factor in wild clam population dynamics unless the clams are subject to unfavorable environmental conditions such as overcrowding, low DO, etc., that increase stress and allow the QPX to proliferate.

Conclusions:

- Planting the appropriate strain will reduce the potential for QPX outbreaks; good husbandry practices are also important in disease prevention in aquaculture settings. Restoration of natural populations should also use the appropriate strains, and site the efforts in areas with good growth.

8. Major clam predators

Predation will be a key factor to consider in future hard clam restoration efforts in the BB-LEH estuary. Table 6 provides a list of predator species known to consume hard clams in the field or in laboratory experiments, and reported in the BB-LEH estuary. These predators, particularly crustaceans, may thus pose a threat to hard clam natural or planted populations. The predator assemblage is typical of other mid-Atlantic estuaries, is highly diverse and may be locally very abundant. A high diversity of clam predators was recently documented within the Sedge Is. MCZ during the spring and summer of 2012 (Bricelj et al., unpubl. data). This included an unusually abundant spring set of starfish, as well as the presence of oyster drills, green crabs, blue crabs and spider crabs throughout the summer. Unfortunately, there is very limited data on the abundance and distribution of the various predators, particularly the smaller more cryptic species such as the xanthid crabs, within the BB-LEH system.

A trawl survey conducted in LEH (Jivoff & Able 2011), reported decapod and fish abundances in 3 habitats: freshwater creeks, eelgrass habitat and deep channel sites. Blue crabs, *Callinectes sapidus*, were found at all sites and were captured consistently throughout the sampling period (June through October), and were thus considered a cosmopolitan species within BB-LEH. Blue crabs were dominant in eelgrass habitat, whereas lady crabs, *Ovalipes ocellatus*, were dominant in deep channels. There was thus both seasonal and habitat-dependent variability in the abundance and species composition of both fish and decapods. At most sites (other than deep channels) both fish and decapods abundance peaked in the summer, as observed in other mid-Atlantic estuaries. Cropping or siphon nipping of siphons by fish in seagrass beds can exert sublethal effects by reducing growth rates of hard clams, presumably due to the cost of regeneration and/or reduced feeding efficiency (Coen et al. 1991, Irlandi 1994).

The role of blue crabs, *Callinectes sapidus*, is highlighted in this report because they contribute to important commercial and recreational fisheries in BB-LEH, and are also major predators of *M. mercenaria* up to relatively large prey sizes (~35 to 40 mm SL) (Arnold 1984, Peterson 1990). Although blue crabs are omnivores and opportunistic predators, hard clams can constitute an important component of their diet in some estuaries and where juvenile, hatchery-produced bivalve seed are released for bottom growout (Kraeuter 2001). Blue crabs prefer to prey in homogeneous substrates (sand, mud/sand combination) rather than crushed shell or gravel. In laboratory experiments predation on hard clam seed was heaviest in the crabs' preferred substrates (Arnold 1983, 1984, Sponaugle and Lawton 1990, Peterson 1990). Thus, substrate type can be manipulated to reduce the crabs' foraging efficiency. Over the decade 1996 to 2006 the percentage of NJ blue crabs landed in Barnegat Bay has risen steadily, from <10% to up to 35% in 2005 (Fig. 41A). There is no clear evidence, however, that the abundance of blue crabs has increased over this same period, although the slight increasing trend in landings was accompanied by a lesser increase in catch per unit effort (CPUE) (Fig. 41B). This may also be due to the area experiencing warmer winters than in the early to middle 1900s which would enhance blue crab juvenile overwinter survival.

In Europe the shrimp, *Crangon crangon*, is considered to be a major predator on juvenile bivalves (reviewed by Kraeuter 2001). Less is known about the effects of the locally abundant *Crangon septemspinosus*. There is evidence that this species is mostly a fall, winter and early spring resident within coastal lagoons. MacKenzie and Stehlik (1988) conducted laboratory studies with *C. septemspinosa* in glass dishes containing 1mm hard clam seed, and found that one adult shrimp consumed all 50 clams in the dish within 24 h. There are no data on consumption of clams in the field, and it is likely that most seed would exceed the size *Crangon* could easily consume by fall, but small overwintering seed may be vulnerable to this predator.

Predation on hard clams is highly dependent on both prey and predator size (declines with increasing prey size), and is also dependent on prey density, as low densities can provide a refuge from predation Reviewed by Kraeuter 2001). Juvenile clams <20-25 mm in SL are the most vulnerable to predators, especially highly mobile crab species, as these show preferential predation on smaller sizes. Burrowing, predatory gastropods such as whelks and moon snails, and starfish, are the most important predators of adult hard clams (> 40 mm in SL). Cownose rays (*Rhinoptera bonasus*) are schooling fish that conduct extensive migrations along the Atlantic coast. They also have adaptations of their jaws, highly calcified tooth plates and hyperdeveloped mandibular muscles, that allow them to feed on hard prey such as *M. mercenaria*, including small adult clams (Fisher et al. 2011, Table 6). These data are consistent with the observations of Kraeuter and Castagna (1980) who reported that cow-nosed rays preferentially consumed cultured hard clams that were approaching littleneck size.

Vulnerability of hard clams of various sizes derived from laboratory experiments must be treated with caution, since they may not take into consideration the effects of other factors that modulate predation rates such as substrate type and alternate prey. Thus, predatory gastropods show preference for thin-shelled bivalves when alternate prey is available. Blue crabs show significantly higher predation in sand than coarse gravel (Arnold 1984), and heterogenous substrate such as sand/gravel and sand/shell is associated with increased prey searching and handling times (Sponaugle and Lawton 1990).

Free-swimming, stinging medusae of the sea nettle, *Chrysaora quinquecirrha*, are not considered important predators of bivalve veliger larvae (Purcell et al. 1991). The medusa adult stage is carnivorous and preys on zooplankton (including copepods, fish eggs and larvae, ctenophores, and other gelatinous zooplankton). Medusae may reduce mortalities of bivalve larvae by consuming ctenophores, *Mnemiopsis leidyi*, which are important predators of veliger larvae (Nelson 1925, Main 1928). Medusae captured and ingested veliger larvae of mussels, oysters and coot clams but did not digest them, such that 98% survived for 24 h following egestion, and 98% of. veliger larvae placed on the medusae's oral arms were rejected. In contrast, copepods were effectively digested when captured and showed low (<2%) rejection by sea nettle medusae. The authors concluded that the closed shell protected bivalve veligers from ingestion and digestion by medusae. A combination of temperature and salinity is a significant predictor of medusa occurrence (Decker et al. 2007). Polyps of *C. quinquecirra*, the sessile life history stage that controls the distribution of this nuisance species, occur in the Cheasapeake Bay within a relatively narrow temperature range (26 to 30°C) and mesohaline conditions (salinities = 10 to 16) (Decker et al. 2007). Thus the presence of sea nettle polyps is largely concentrated in the northern sector of Barnegat Bay, an area of comparatively lower salinities due to the freshwater inputs of the Metedeconk and Toms Rivers (Guo et al. 2004; Bologna 2011). However, a recent study found that polyps may also occur in coastal lagoons along central BB (P. Bologna, Montclair State University, NJ, unpubl. data). It is noteworthy that sea nettles are also tolerant of low DO levels associated with eutrophication (Decker et al. 2007).

<u>Conclusions:</u>

- Clam seed are preyed on by a wide variety of predators, and crabs are generally the most important.
- Predation rate declines as clams grow, and by ~25 m SL losses are typically reduced. The only large predators capable of consuming littleneck and larger clams are whelks, seagulls (intertidal zone), cow-nosed rays and man. Of these the latter two are capable of greatly depleting the local stocks.
- Substrate type interacts with predators to affect recruitment. Fine grained sediments may erode shell material and make newly set clams more vulnerable to predators. Sandy and muddy sediments of uniform grain size appear to have higher predation rates than mixtures, and those with admixtures of shell, sand and mud appear to provide the optimum for survival.
- Only a small fraction of hatchery-reared seed can reach a size (22-25 mm SL) at which they are less vulnerable to predators in one season. This implies that where seed broadcasting is implemented, most seed will have to maintained for most of the second summer under protective mesh, or grown to larger sizes in hatcheries if future advances in algal production technology become cost-effective, before they can be broadcast throughout large areas.

9. Clam aquaculture and restoration

9.a. Hard clam stock enhancement in BB-LEH

Low-intensity efforts at restoration of hard clams via seeding and habitat improvement have been undertaken in the BB-LEH. Kraeuter et al. (2003) reported on a 10-year shelling experiment designed to increase hard clam recruitment in BB. This study indicated that hard clam populations could be enhanced by shelling, and the effects were dependent on the amount of shell. Broken pieces of ocean quahog shell were obtained from a shucking house and spread at two densities (900 bu in a 20 x 70 m plot = high density (15 L of shell m^{-2}) and 300 bu in a similar sized plot = low density (5L of shell m^{-2}) in a 3 x 3 Latin Square design. Thus there were 3 high-density, 3 low-density and 3 control (no shell) plots. Initial results indicated that both shell densities enhanced recruitment, but after 8 years the lower shell density was no different than the control. Shelling of 8 to 12 Kg of shell m^{-2} increased recruits from < 1 clam m^{-2} to nearly 5 recruits m^{-2} and doubling that density to 16-26 Kg m^{-2} increased the density of recruits and of total clams to nearly 8 m^{-2}. (Kraeuter et al. 2003). This study clearly indicated that hard clam populations could be enhanced by shelling, and that the effects were dependent on the amount of shell deployed. (Fig. 42) The shell remained active for a number of years that was dependent on the initial shelling density.

The Barnegat Bay Shellfish Restoration Program (BBSRP), a collaborative endeavor involving Rutgers Extension of Ocean County, the NJDEP Division of Fish and Wildlife, the non-profit organization ReClam the Bay Inc. (RCTB), and the American Littoral Society has been conducting shellfish restoration activities in Barnegat Bay since 2005 (http://ocean.rcre.rutgers.edu/marine/bbsrp.html).

With an emphasis on hands-on training and on-the-ground small-scale shellfish restoration activities, BBSRP focuses primarily on environmental education and stewardship through demonstration of nursery production and subsequent planting of hard clam seed at selected sites. ReClam the Bay volunteers maintain waterfront, land-based upwellers/silos adjacent to dock locations, that are used for the nursery growout of small seed up to planting sizes. The upweller units pump ambient water [~ 227 L (60 gallons) min^{-1}] directly from the bay (Fig. 43, www.reclamthebay.org). Each nursery unit typically consists of a 2.44 x 1.22 m (8 x 4 ft) tank, containing 10 to 16 45.7 cm (18”) silos. They are stocked with 2-4 mm clams at ~ 30,000 clams per silo in the early summer and grown until they attain ~ 8 to 15 mm prior to their release in the bay in the fall. Weekly records are kept of the volume per 100 clams and total volumetric count at all sites allowing a rough comparison of seasonal production between sites. These data are not intended and cannot be used to estimate clam growth rates for a given cohort, however, as the mean size of clams over time is not measured, the biomass per silo can vary, and different source of hatchery seed may be used at different sites. The data generated do not provide survival estimates. The nursery units are located at 8 sites throughout the BB-LEH, from north to south at: Island Beach State Park Marina, Barnegat Light Municipal Boat Ramp, Waretown where ReClam the Bay also operates a bottom lease for overwintering of hard clams, Surf City Yacht Club, Mantoloking Yacht Club, Brant Beach Yacht Club, St. Francis Center, and Beach Haven (former Coast Guard Station). Posters at these locations inform the public of their activities. Over the first 8 years since its inception in 2005, BBSRP raised over 10 million clam seed and 3 million oyster seed as part of its nursery operations. Since its inception, BBSRP has experienced considerable growth in terms of volunteer members, number of shellfish grown, press coverage and support for local businesses.

In the context of restoration, once grown to a suitable size, clams are deployed in the MCZ and other selected locations throughout the bay where they are covered with predator control screen. Seed clams without predator control, are also planted in public areas (3 locations in Barnegat Bay) for conservation and or eventual recreational harvest. The seed clams planted under screens are removed after one year and broadcast planted in areas designated by NJDEP. Results of this enhancement effort remain to be analyzed and published, and the overall enhancement effort has not been rigorously evaluated to date.

In parallel with BBSRP activities, the NJDEP Division of Fish and Wildlife has been conducting hard clam restoration activities within the Sedge Is. Marine Conservation Zone (MCZ) (Fig. 44), a 600 acre (2.43 km^2) zone with SAV cover over approximately half of this area. Commercial clam harvest is not allowed in the MCZ but recreational clamming is permitted. The magnitude of this recreational harvest activity has not been assessed to date, although a first survey has been initiated by NJDEP in 2012 using standard questionnaires. To date over 15 acres (0.061 km^2) of shallow water habitat have been seeded with >3.7 million hatchery produced clams in the size range of 15-30 mm SL, and broadcast at a density of 10 clams m^{-2} over habitat mostly comprised of sand/mud substrate with areas of sparse SAV. Planting effort in 2010 and 2011 (spring and fall plantings) is shown in Table 7, when a total of 2.16 million 20-25 mm SL seed were broadcast in 2 acre plots at densities ranging from 13 to 24.7 clams m^{-2} (Calvo 2011). Densities of clams prior to planting ranged from 1.3 to 9.3 clams m^{-2} but resident clams were $\geq$ 55 mm SL and thus distinguishable from smaller newly planted clams. Clam sampling following plantings in late fall 2010 was again conducted in the spring (May 2, 2011) and in the summer (July 21-28) of 2011 using hand rakes with a 7/8" (22.2 mm) basket mesh opening, to determine survival and growth. Planted clams attained a mean SL of ~ 30 mm by late July 2011. Mortality (and growth) estimates may be confounded by the fact that the areas planted were exposed to an unknown magnitude of recreational clamming. Additional analysis of the data derived from these seeding efforts in the MCZ awaits completion and is at present unavailable in published form for our evaluation as part of this report.

This seeding effort has shown promising results. For example, the larger sized seed (≥18 mm) have exhibited a high survivorship (≥74%) and excellent growth with a high proportion of clams attaining 1.5" (3.8 cm) SL within 1 year. Prior efforts in North Carolina to replenish depleted hard clam stocks with hatchery seed production demonstrated the importance of a combined approach employing large size seed clams, low planting density, optimal planting season and suitable bottom type to minimize predation and ultimately contribute to establishment of the stock (Peterson, 1990).

A seeding trial using 1 million 1-yr old juveniles averaging 23.6 mm) was also conducted in Great Bay by the Division of Fish and Wildlife in early May 2010 over 23 acres (0.09 km^2) of unvegetated, predominantly firm sand to avoid potential effects of clam harvesting on SAV (Calvo 2012). A survey conducted in late August 2011 with a hydraulic dredge with a cage lined with a 1/2" (1.3 cm) mesh indicated that pre-planting clam densities that were 0.16 clams ft^{-2} (1.72 m^{-2}) had approximately doubled to 0.39 clams ft^{-2} (4.2 clams m^{-2}) 16 months following planting.

A seed size class of ~ 20-26 mm has also been used in the past for bottom seeding by the Town of Islip in Great South Bay, NY, as it provides partial size refuge from a wide range of clam predators, including mud crabs (Table 6). At this size, however, clams can still be preyed upon by blue crabs, moon snails, whelks and starfish that occur within the BB-LEH estuary. Results of the Long Island Towns' seeding activities indicated that survival rates following seeding in unprotected bottom were greatest when clams were stocked at sizes of 26 to 30 mm SL and at densities of 10 clams m^{-2} (LoBue 2010). Seeding is typically undertaken in the fall, when crab predation is declining, but when temperatures are high enough for clams to dig into the sediment.

The creation of spawner sanctuaries has been another strategy used to restore hard clam populations in mid-Atlantic estuaries. This approach involves transplanting of adult clams from areas of higher abundance to depleted areas protected from harvest, so that their spawning may increase the chances of successful recruitment. Chowder clams are typically used as they have the lowest dollar value of commercial size classes, and under appropriate food conditions generally have high fecundities. Spawner sanctuaries were first implemented for hard clams in Great South Bay, NY, in the 1980s, and adopted in BB-LEH in 1986 (McCay 1988). Chowders from multiple sources (~219,000 painted individuals to limit poaching) were released at two sites in May, one near the town of Barnegat in southern BB, and another in Parker Cove, LEH. The latter was deemed more likely to succeed because this area once had productive clam beds and circulation conditions were more conducive for larval retention (see Carriker 1961). Both sites were also selected because of their ready access from shore, that facilitated monitoring by enforcement officers.

This effort had limited success in enhancing the local clam population. There were difficulties in obtaining the clams, initially intended to originate from polluted waters in Raritan Bay, NJ, conflicting interests and agendas among groups involved in this co-management project, regulatory and enforcement issues, and the participants were unable to obtain funding for a sustained, large-scale effort (McCay 1988). Many of these issues remain valid today. The participants in this early spawner sanctuary project included clammers, NJDEP personnel, scientists from academia and government, and extension personnel. The clams that were planted were scarce soon after planting at the BB site due to the high levels of illegal clamming. In turn, clams planted at the LEH site showed suppressed gamete production suggesting that environmental or nutritional conditions were inadequate for reproduction (Barber et al. 1988, cited by McCay 1988). The limited scale, poaching, and inability to rigorously evaluate the outcome of spawner sanctuaries were also important contributors to the lack of success of these earlier efforts. This is in opposition to the apparent success of utilization of numerous dispersed spawner sanctuaries in Great South Bay, NY (Lo Bue, 2010). It is important to note that while hydrodynamic models of this system are available, they were not utilized in the placement of these beds. While these models are useful to describe general circulation patterns, they fail to integrate two important aspects of bivalve recruitment. The first of these is the wide range of times and locations over which spawning takes place during a given annual spawning season, and over the lifespan of a typical spawner. This general location effect is further complicated by the unknown wind-driven circulation that can affect larval distribution over the relatively short larval life, and behavioral responses that are not described by models that use buoyant inert particles and dyes as tracers of bivalve distributions. This combination means that over the course of a season or several years, larvae can potentially reach almost all parts of the bay. More importantly, evidence from many bivalve species indicates that recruitment success is driven more by post settlement survival (mostly in the first year of life or less when highly vulnerable to predators), than by larval supply (e.g. Gosselin and Quan 1997). This important aspect is not incorporated in these models.

9.b. Hard clam stock enhancement in Great South Bay, NY.

Much larger scale hard clam restoration efforts have been conducted by The Nature Conservancy (TNC) in Long Island, NY, which acquired 13,000 acres (52.6 km^2) of submerged lands in central Great South Bay (GSB), in 2003 (LoBue 2010). The stated purpose of this activity is "to restore a robust, self-sustaining hard clam population by 2020 for the purpose of ecosystem health and sustainable harvest". The aim was to achieve an average density of 6 clams m^{-2} by 2010. The Bluepoints Bottomlands Council, a body comprised of government agencies, scientists and community stakeholders identified four major obstacles to clam population recovery in GSB: harvest, predation, recruitment limitation, and water quality/clam food.

The TNC, in contrast to earlier efforts by GSB townships and the Bluepoints Co., did not adopt seeding of hatchery-produced clams as their main restoration strategy, but focused primarily on transplanting of reproductive adults in areas protected from harvest. Although seeding was recognized as a valuable tool in restoration under specific scenarios (e.g. localized stock enhancement, development of disease-resistance in shellfish highly prone to disease), their rationale was based on the fact that prior seeding efforts had not proven successful in restoring natural populations, and that clam hatchery production would lead to low genetic diversity (LoBue, 2010). The economic feasibility of producing enough clam seed to make a significant contribution to the natural population, especially given the high losses of seed to predators, was discussed by Malouf (1989).

A clam survey conducted by TNC in central GSB in 2004 indicated that clams $\geq$ 20 mm SL occurred in low abundances (averaging ~ 0.18 clams m^{-2}) (LoBue 2010). Between 2004 and 2009 TNC transplanted 3.7 M adult clams over 60 acres in central GSB at a target density of 10 to 20 clams m^{-2}. Clams originated mostly from western Long Island Sound (NY and CT waters) and were planted the same day or one day following harvesting. Spawner sanctuary locations, typically $\leq$ 1 acre in size, were selected to avoid areas with muddy sediment, those where poaching is more likely, and inlets to reduce larval export. Mechanical harvest was eliminated over the conservation area to provide the clams with refuge from harvest. Local townships are responsible for maintaining sustainable harvesting efforts in their own GSB jurisdictions to prevent overharvesting. Planting of adult clams by TNC was attributed as the cause of a strong 2007 cohort, associated with an increase in the number of sublegal clams $\geq$ 7 mm SL in this sector of the bay from 0.08 clams m^{-2} in 2006 to 3.5 clams m^{-2} in 2008. The contribution from spawning of adults from neighboring waters, primarily Babylon Town waters, western GSB, which retained moderate densities of adult clams in 2004 and sustained a small recreational and commercial harvest, remains unknown.

Although there is a great deal of uncertainty in field-derived hard clam mortality estimates, Lo Bue (2010) reported highly variable mortalities of stocked clams among spawner sanctuaries, ranging widely from 0 to 77% at 29-33 months following transplant. Mortalities were determined from the proportion of live to total number of stocked clams based on diver observations in areas that were stocked only once. Mortalities were attributed to post-transplant stress, predation by whelks and winter mortalities following a year of severe brown tide (2008), when adult hard clams exhibited very low condition index. Another finding was that years when the phytoplankton was dominated by small forms (< 5 μm) during the clams' growing season (spring, summer and fall) were associated with conditions that did not yield good spawning events and clam growth. Thus strong spawning events occurred in 2006 and 2007, whereas spawning was greatly reduced in 2008 and 2009 due to brown tide. The recommendation from these efforts was that it would be necessary to maintain > 2 M live adult clams spread over multiple (50) moderately high density areas to enhance recruitment (LoBue 2010). From fall 2007 to Dec. 2009 both native and transplanted clams in GSB exhibited lower condition than in other NY estuaries, e.g., Shinnecock Bay, as well as estuaries that provided the source of transplanted clams in western Long Island Sound i.e., Greenwich Cove and Oyster Bay. This was attributed to the dominance of the phytoplankton biomass by < 5 µm cells (sometimes but not always caused by *A. anophagefferens*) during the summer and fall, as well as low concentrations of centric diatoms during the spring, summer and fall, relative to other local estuaries (see sec. 3a.).

Conclusions (sec. 9 a and b):

- Two main strategies have been used in the past to enhance hard clam populations in mid-Atlantic coastal bays: a) seeding of juveniles at sizes greater than ~ 25 mm SL that provide them with protection from most of their predators, and b) planting of large reproductive adults (chowders and cherrystones) within areas designated as spawner sanctuaries that are protected from harvest.
- Plantings of multiple areas at moderately high densities (~5 m^{-2}) are deemed a better strategy than planting a larger area at low densities (less than ~ 0.6-0.8 clams m^{-2}) that may limit recruitment.
- Hard clam stock enhancement efforts have so far met with mixed success due to a) biological obstacles (e.g. brown tide in GSB, NY), and b) in BB-LEH, poaching and especially funding-political obstacles that limited the continuity of these efforts at a scale sufficient to make a significant contribution towards enhancement of natural populations.
- Stock enhancement efforts need to set realistic targets, and especially allow for rigorous evaluation of programmatic goals over a period commensurate with the population dynamics of the species within the system.
- Stock enhancement will need to be accompanied by a concerted stock monitoring and management plan for the hard clam resource in the BB-LEH. Ideally this will include stakeholders, scientists and both local and state representatives.

9.c. Overwintering mortalities of clam seed

A major challenge to hard clam restoration activities in northeastern and mid-Atlantic waters is the mortality of clam seed during their first winter and following spring. This mortality can be highly variable, ranging from 5 to 100% in laboratory and field studies (Damery 2000, Aldred et al. 2000, Bricelj et al. 2007, Weiss et al. 2007, Zarnoch and Schreibman 2008), and is site- and size-specific. Hatcheries produce clam seed to sizes suitable for planting, between 8-15 mm SL, by late summer or early fall, such that most seed do not reach 20 mm by fall, yet small seed (<20 mm) are generally more susceptible to overwintering mortalities. Laboratory and field predator exclusion studies indicate that mortality during and following the first winter is attributable to physiologically/biochemically-based starvation (see below) and/or a combination of starvation and subsequent bacterial infection. Crustacean predation is likely to further contribute to these mortalities in the field (Kraeuter 2001). These early mortalities are a major impediment to the hard clam aquaculture industry and restoration efforts, since for the latter, the purchase of hard clam seed is one of the largest capital costs.

Therefore shellfish management programs, including the BBSRP, have aimed to use clams exceeding this size in order to minimize losses. The tradeoff is that fewer numbers can be produced due to the constraints of labor, culture equipment, and space. There is also evidence of non-predatory mortality occurring in planted populations of clam seed during and immediately following the winter months (so-called “winterkill”), attributed to severe winter temperatures both in the Mid-Atlantic U.S. and Canada (Bricelj et al 2007, Zarnoch & Schreibman 2008). Overwintering mortality has not been systematically quantified in large scale field experiments despite its significant effects on clam restoration programs due to the labor costs required, leading to limited ability to assess the success and associated economic an ecological impacts of their efforts.

Juvenile hard clams use primarily or almost exclusively carbohydrate reserves to fuel overwintering energy demands (Bricelj et al. 2007, Zarnoch & Schreibman 2008). At temperatures ≤ 5°C, active feeding by hard clam ceases, and this places a metabolic burden on their energy stores. This leads to utilization of carbohydrate reserves presumably below a critical threshold that likely contributes to winter/spring mortalities. The condition of clam seed in the fall, and the temperature and food levels during the subsequent spring have been shown to be critical in determining the mortality levels of clam seed. Physiological stress at low temperatures may also provide an entry to bacterial pathogens (Kraeuter and Castagna 1984).

Lipid membrane composition could also be an important determinant of clam overwintering survival, given the linkage between membrane fluidity, polyunsaturated fatty acid (PUFA) levels in membranes, and adaptation to low temperatures (Hall et al. 2002, Hochachka & Somero 2002). Pernet et al. (2007), using the same source of clams as Bricelj et al. (2007), showed that *notata* juveniles differed in their lipid metabolism from “wild”, unselected juveniles. They found that phospholipid to sterol ratios, an indicator of membrane fluidity, and an adaptive response to low temperature stress, in “wild” juveniles increased up to 2.6-fold between August and October, whereas this ratio remained constant in *notata* individuals. The makeup of membrane (phospholipid) PUFAs is determined during the fall when clams are still actively feeding, and remains relatively stable during the winter (Bricelj & Pernet, unpublished data). Differences in lipid composition and in phospholipid to sterol ratios, an indicator of membrane fluidity and an adaptive response to low temperature stress, were also associated with the higher vulnerability of cultured clams to overwintering mortalities relative to wild seed (Pernet et al. 2006).

Clams of the *notata* genetic variety (Fig. 45) are often selected for production in commercial hatcheries due to their distinct, heritable shell markings which are rare in natural populations. Laboratory (Bricelj et al. 2007) and field studies (Zarnoch and Sclafani 2010) show that they suffer significantly higher overwintering mortalities than “wild”, unselected clams. There is additional evidence, from an ongoing study sponsored by The Northeast Regional Aquaculture Center (NRAC), that implicates genetic/physiological selection in the clam stock’s ability to survive overwinter conditions. In this study seed clams (7 to 9 mm) of Maine, New Jersey and New York strains were held in mesh bags at all three locations over two winters, and the local strain was planted in field plots. At all locations in both years the ME seed survived better than either the NY or NJ stocks in the bags. Clams planted in field plots had higher survivorship (field survival for NJ seed in NJ in year 2 was 14% and 45% for the two size classes deployed in field plots, and only 2% and 18% respectively, in bags. Data for NY are similar (unpublished data) Analysis of these data is still in progress and further work is needed to elucidate the mechanisms underlying this resistance. Advanced genetic technologies, e.g., transcriptomics analysis, could provide a powerful tool to determine the genetic basis for differences in susceptibility to overwintering mortality among various *M. mercenaria* stocks.

Conclusions:

- Overwintering survival of hard clams is size-dependent, typically affecting seed < 20 mm in SL. Recent experiments have shown that field plantings (under protective mesh) provide better survival than holding the animals in mesh bags.
- Overwintering mortalities have been found in independent studies conducted in Canada and the US to be significantly greater for hatchery produced *notata* seed than for "wild" seed. The genetic and physiological basis for this difference remains unknown.

10. **Bottom Leasing in BB-LEH**

Subject to approval by the Commissioner of the NJDEP, the Atlantic Coast Section of the NJ Shellfisheries Council is granted exclusive power to lease lands under the tidal waters (Atlantic coast) of the State for the planting and cultivation of oysters and clams. There are a number of restrictions on shellfish leasing. Thus, according to the Atlantic Coast Leasing Regulations, leasing is only allowed in areas classified as not productive for shellfish. There has also been a long-standing Department and Council policy of only allowing new lease applications to apply for parcels adjacent to existing leases for reasons of enforcement and user group conflicts. Leasing is also not allowed in areas designated as SAV habitat. A biological investigation of the lease area must be conducted by the Bureau before the Council can make a decision on a lease application. Given this requirement, the leasing process can provide useful information on resident fauna and habitat characteristics relevant to this report. Existing leases by sector in BB-LEH, in addition to areas used in the past for relaying, and vacated lots are shown in Fig. 46A to E.

A shellfish lease application for 30 two-acre leases divided into two block sections (northern and southern) in Middle Island Channel, southern LEH (Fig. 47) which had not been previously leased, was submitted in 2008 by multiple growers (Normant 2009). This led to a bottom survey of this area during the summer of 2009 by the Bureau to determine hard clam densities and size structure of the clam population. Sampling was conducted using hand rakes in shallow waters, with the basket lined with a 30.5 mm (1.2") wire mesh. The teeth of the rake were 3" long and the width of the rake was 1.48'. A hydraulic dredge with bars spaced to retain clams ≥ 30 mm (50 ft tows), was used in deeper waters. A subset of stations that were sampled with rakes was also sampled using a suction dredge that extracted sediment to a depth of 4", and was used with a 3 mm mesh bag placed at the outflow. Additionally, a Peterson grab sampler which samples the top 1-2" of the bottom in mixed sand/mud substrate, was used to sample juvenile hard clams collected on a 1 mm mesh sieve. Salinities during the survey period ranged from 30 to 32, DO from 7.1 to 7.4 mg l^{-1}, and pH from 8.0 to 8.2. Depth of the water column ranged from < 3 ft (0.91 m) over most of the area, to a maximum of 17 ft (5.2 m.

Clam densities at the various sampling stations are shown in Fig. 47. Overall, for the whole area surveyed, the mean density was 0.6 clams ft^{-2}, and ranged between 0 and 0.98 clams

ft^{-2}. In shallow waters densities ranged from 0 to 0.47 clams ft^{-2}, and in deeper waters densities averaged 0.11 clams ft^{-2} and ranged between 0 and 0.98 clams ft^{-2}. Thus, higher clam densities were found in shallow waters than in deep waters, but a larger percentage of the area surveyed in shallow waters (62%) yielded no clams when compared to that of deeper waters (25%) (Fig. 48), although it is important to note that different sampling gear was used in the two habitats. Overall, combining both rake and hydraulic dredge sampling, the southern lease block had higher mean and maximum densities (mean = 0.09 clams ft^{-2}, range = 0 to 0.98) than the northern lease block (mean = 0.94 clams ft^{-2}, range = 0 to 0.41). Overall a total of 5.47 acres and 1.91 acres were identified as having moderate and high hard clam densities respectively within the surveyed area (total area = 63.5 acres). Thus only 11.6% of the total area was deemed capable of supporting commercial hard clam harvest.

The Middle Island Channel hard clam population exhibited a broad size-frequency distribution, with multiple year classes, indicating that the area had a history of natural recruitment (Fig. 49). Young clams, 2008 and 2009 year classes, were represented, indicating recent recruitment.

This survey also identified other macrofauna present, although these were not enumerated or sized. Clam predators identified included the mud crab (*Dyspanopeus sayi*), blue crab (*Callinectes sapidus*), hermit crab (Pagurus spp.), lady crab (*Ovalipes ocellatus*) and spider crab (*Libinia emarginata*) (see Table 6 for the vulnerability of clams of various sizes to these predators). Other clam predators present were the channeled whelk (*Busycotypus canaliculatus*), knobbed whelk (*Busycon carica*), lobed moon snail (*Neverita duplicata*), seastar (*Asterias forbesii*), and horseshoe crab (*Limulus polyphemus*). Other suspension-feeding bivalves identified in the surveyed area included the blue mussel (*Mytilus edulis*), false quahog (*Pitar morrhuana*), razor clam (*Ensis directus*), purplish Tagelus (*Tagelus divisus*), blood ark (*Anadara ovalis*), and surf clam (*Spisula solidissima*).

Other lease surveys for individual leases have been conducted over the years. We have compiled the BB-LEH lease survey information from NJDEP records and the data are provided in Appendix I. These data are only for the most recent time period, and there are significant number of leases that predate the existing records. We also provide a list of clam surveys that were conducted by NJDEP as a result of shoreline development activities. These data are shown in Appendix II.

<u>Conclusions</u>:

- There is evidence from a lease in Middle Is. Channel, southern LEH, where clam densities averaged 6 clams m^{-2} (0.6 clams ft^{-2}) that natural recruitment has occurred in recent years at this site. However, only a small portion of the lease area (12%) was deemed capable of supporting commercial clam harvesting.

11. Management of the hard clam resource

In NJ shellfish harvesting is regulated by multiple agencies within the NJDEP, and management of the shellfish resource takes place at the state level. In 1982 a Coastal Bay Clam Resources Task force was formed by the NJ General Assembly (Joint Resolution No. 21). This group "which shall study and formulate policies to protect, preserve, enhance and promote the development of the *[commercial]* *bay* shellfish industry in this State, and which shall report its finding to the Legislature thereon, including recommendations for possible State action." This committee was chaired by Kirk Conover. Voting members were: Dr. Harold Haskin, James Jenks, Newman Mathis, Stuart Tweed, George Kovaleski, Jack Parsons, Frank Randall. Non-vot ing members were: John Hendrickson, Thomas Pankok (Both Assemblymen), Bruce L. Freeman, NJDEP, Nils Stolpe, NJ Dept. Ag. and Kenneth Kolano, NJ Dept. Health. It is useful to review the recommendations to determine how they correspond to current views.

For Enforcement:
1. Increase fines for illegal harvest of seed clams
2. Increase fines, institute jail sentences for condemned water violations.
3. Increase enforcement of health regulations concerning sale of clams to certified dealers.
4. Institute a clam warden system within the marine enforcement unit of DEP.
5. Increase clam license fees with increased revenue dedicated to enforcement and management of the clam resource.

For Pollution Control:
6. Require City of Egg Harbor to tie into Atlantic County Regional Sewage treatment plant.
7. Investigation of reports of non-point pollution.
8. Continue funding for NJ 208 projects and studies of prevention of non-point pollution.

For Regulatory Changes:
9. Reduction of the hard clam (sic clam) relay lease fee from $50.00 to $5.00.
10. Support Assembly Bill No. 128 to protect commercial dock space by tax abatement.
11. Create a division of mariculture within the DEP with the consultation of the Department of Agriculture, dedicated to enhancement and promotion of the clam resource.

For Marketing:
12. Develop a “Jersey Fresh” marketing program for clams, along the lines of the agriculture promotions for farm produce.
13. Include clams in produce offered at farmers markets in the Meadowlands and Camden.

For Biological Enhancement:
14. Protection and management of clam populations in naturally productive areas.

In discussion it was noted that there was a belief that the NOAA statistics significantly under-reported hard clam landings and a survey of licensed commercial fishermen estimated the NJ landing were 52.1% greater than the NOAA data indicated. Because of the inadequacies within the NOAA reporting system, under or bypassing of the reporting system by aquaculture product is probably as prevalent today as it was in the 1980s.

Current general state regulations pertaining to shellfish and thus also relevant to *M. mercenaria*, include (http://www.state.nj.us/dep/fgw/shelhome.htm):

- Shellfish shall not be taken from condemned waters without appropriate permits (as in the case of special restricted waters) or during the closed season (as in the case of seasonal waters). Pursuant to N.J.A.C. 7:12-1 et. seq., condemned areas are comprised of the following classifications: Prohibited, Special Restricted, Seasonal Special Restricted and Seasonal (when seasonally closed to harvesting) (see sec. 5a). Penalties for harvesting shellfish in condemned waters could result in the possible seizure and forfeiture of boat and equipment and a loss of license for a period of three years for a first offense.

- Shellfish growing water classification charts are revised annually and can be obtained (at no charge) from shellfish licensing agents or at www.nj.gov/dep/wms/bmw. Shellfish cannot be taken before sunrise or after sunset. Shellfish cannot be taken on Sunday except in the waters of the Raritan Bay, Sandy Hook Bay, Navesink River and Shrewsbury River during the shellfish water classification open period (consult shellfish growing waters classification chart for those areas open to harvest). A license is required for the commercial harvest of shellfish.
- Shellfish harvested can only be sold to Certified Dealers (or used for personal consumption). Licensee is required to have the appropriate license on his/her person at all times while operating under said license.
- Stakes are used to mark leased grounds. Harvesting within these lots is restricted to the lessee or his designee. Maps of leased grounds on the Atlantic Coast are on file at the Nacote Creek Shellfish Office, 360 New York Road, Route 9 North (Milepost 51), Port Republic, NJ. Maps of leased grounds in Delaware Bay are on file at the Delaware Bay Office, 1672 E. Buckshutem Road, Millville, NJ 08332.

Current state regulations pertaining to molluscan shellfish, including *M. mercenaria,* but excluding conchs and whelks:

- The minimum size for hard clams is 1-1/2 inches (longest dimension). It is illegal to harvest shellfish by any mechanical means or motor power.
- All harvesting on public grounds is restricted to the use of hand implements only. Whenever a person is in possession of a commercial shellfish license in any vessel or vehicle and is engaged in any shellfish activity, all other persons harvesting clams on or in that vessel or vehicle shall also possess a commercial shellfish license.
- Commercial Shellfish License: $50.00 per license (Resident); $250 per license (Non-resident).
- Recreational harvest size limit = 1.5 inches (longest dimension). It is illegal to harvest shellfish by any mechanical means or motive power – all harvesting on public grounds is restricted to the use of hand implements only. No Sunday harvest. Recreational license = $10.00, Senior (65 years) life-time license $2.00, Junior license $2.00.

While authority for management of the hard clam resource resides within the NJDEP there is no overall management for this historic and valuable fishery. While there was an effort to survey the population in the 1980s using Federal funds, the survey did not reach the lagoonal systems in the southern part of the state. In addition, only two areas have been resurveyed since the 1980s and those are Raritan/Sandy Hook Bays at the end of the 1990s and the Little Egg Harbor portion of the BB-LEH estuary in 2001. Two surveys were recently completed, in LEH in 2011 and Lower Barnegat Bay in 2012 and results should be available soon. In order to effectively manage the resource there is a need for good population information on a timely basis. Given that studies have suggested that the population turnover of hard clams in BB-LEH is on the order of 8-10 years, management would require multiple surveys during that time period to make informed decisions.

<u>Conclusions</u>:

- In contrast to restoration efforts conducted in GSB, NY, the goals of hard clam restoration efforts conducted in BB-LEH to date have been small-scale and primarily educational (see sec. 9a & b). With currently available information, there is no way to assess the status of the stock or the effects of restoration efforts given the limited temporal scale of the basic survey information and the lack of rigorous evaluation of current seeding activities.
- In spite of the importance of the hard clam to many harvesters in the State of New Jersey there has never been an attempt to develop an overall management plan.
- There are ample areas [e.g. the MCZ (see sec. 9a) and sectors of LEH (see sec. 10)] that could be used for aquaculture production to augment the existing wild fishery. Given the low and stochastic recruitment of hard clams in BB-LEH, a temporally reliable source of hatchery-produced seed for outplanting under protected conditions would provide a critical way to supplement the wild resource.

The primary impediments to stock enhancement, expanding aquaculture and resource restoration at scales that will likely have a significant impact in the estuary appear to be lack of concerted initiatives on the part of the State and local jurisdictions within the BB-LEH system. Clam aquaculturists in NJ are generally supportive of restoration in the BB-LEH and provide the source of seed used for such efforts. Local municipalities along the estuary also have an interest in clam restoration but have no authority to initiate this effort.

12. Overall Conclusions, Identification of Knowledge Gaps and Recommendations

Key conclusions, recommendations and research needs are provided at the end of individual sections throughout the text. A few additional summary conclusions and recommendations are highlighted below.

12.a. Overall Information Gaps

- The lack of a coherent, comprehensive monitoring plan for hard clams has greatly limited the usefulness of the information that is available. There are towns in NY that have annually spent more funds assessing their hard clam populations than has the entire state of NJ. The cost associated with a carefully designed, sustained monitoring effort in key areas of the bay will need to be weighed against other monitoring and research priorities.

- So far limited attempts at development of a clam management plan (sec. 11) for such a valuable and iconic resource are to be deplored. The state and each of the towns along the bay might consider jointly funding a third party group to make an annual or bi-annual assessment of the BB-LEH hard clam resource as this is necessary to determine temporal changes in natural or enhanced populations.

- Without current and ongoing information on the status of the resource no scientific statements will be possible concerning overall population trends and the progress of any rehabilitation efforts.

12.b. Rehabilitation

- **Clear definition of the scale and goals of rehabilitation of hard clam populations is essential (provision of ecosystem services, enhancement of recreational fishing, public awareness, supply of broodstock for aquaculturists, etc). Implementation of a stock restoration effort will also require rigorous evaluation of recent and newly proposed restoration activities in the BB-LEH.**

- Although based on very limited surveys (this report excludes 2011/2012 surveys that are yet to be analyzed), the low densities of hard clam populations in BB-LEH and the dominance of larger size classes suggest that a concerted stock enhancement effort will be needed to augment current population levels.

- If the system is recruitment limited due to low population density, then establishing and maintaining multiple areas of moderate (~ 5 clams m^{-2}) density of adults will likely enhance overall recruitment.

- The BB-LEH system already has tens of millions of clams and unless the annual rehabilitation efforts can approach this level, the net result will be undetectable. It is also possible that the existing population has adequate spawning capacity to result in enhanced fishery-level recruitment if the environmental factors decreasing early survival are identified and eliminated. Existing information is insufficient to rule out this possibility.

- Sanctuary areas for both adults and/or seed need to be established where harvest is prevented. Protection of seed from predators via substrate manipulation or other strategies will be essential to counteract the high mortalities experienced at small sizes ($\leq$ 20-25 mm SL).

- Allowing aquaculture areas will also provide additional hard clams to the system, and although these animals are typically harvested before they spawn more than a few years, they are replaced annually with no cost to the state. One strategy could involve paying clammers to maintain some portion of the planted stock on the bottom and thus ensure their participation in such programs.

- An overall, all encompassing rehabilitation plan including areas for aquaculture, commercial and recreational harvest, no take areas, and a clear sampling plan, with analysis/comparison of the efficiency of various sampling methods (e.g., rakes, tongs, dredges) to assess progress is sorely needed.

12.c. General Study Needs

- Studies focused on the determination of site-specific hard clam natural recruitment and mortality rates in the estuary should be encouraged. The evidence of increased mortality in the LEH adult clam population, and the extensive areas where clams were not found in the 2001 surveys, suggest that a study to determine whether this mortality is due to an ongoing issue/s or a singular event should be initiated. This, while extremely challenging bay-wide, could be critical to rehabilitation efforts in localized waters.

- Determination of specific areas within the estuary that support good somatic and reproductive growth (the same areas may not necessarily support both) is necessary and highly amenable to study.

- No information is available on the reproductive output and effort of hard clams in the BB-LEH, or on gamete quality, which could be important factors controlling clam population dynamics, especially given the low densities of adults reported in the most recent surveys. Since the establishment of spawner sanctuaries is one management option for consideration to enhance hard clam stocks in BB-LEH, it is important to determine the magnitude and variability in the hard clams' reproductive output in relation to environmental conditions, especially the food supply.

- The BB-LEH system has been prone to brown tides of *Aureococcus anophagefferens*, a picoplanktonic alga that can cause deleterious effects on hard clam populations at levels an order of magnitude below those that cause discoloration of the water ($2x10^5$ cells ml^{-1}). Monitoring for *A. anophagefferens* should be included in routine phytoplankton monitoring programs using the immunofluorescence method or other highly specific method. Aerial surveys are insufficient.

- There is no evidence that increasing eutrophication, or the decline of SAV habitat have **direct** deleterious effects on hard clam populations in BB-LEH, or that they contributed to the historical decline of clam populations in this system. Eutrophication and/or shifts in nutrient ratios and changes in other environmental conditions can lead to proliferation of microalgae that are harmful or a poor food source for hard clams. Bulk Chl *a* measures alone are inadequate to assess changes in phytoplankton composition and should be supplemented with other methods.

- Even relatively large hard clam seed (greater than ~ 20 mm) can be vulnerable to predation. It will therefore be important to assess potential methods of enhancing recruitment and survival of clam seed to predators in different habitats (e.g. different substrate type including shell cover, presence and density of eelgrass beds), in the BB-LEH.

- Modeling of hard clam population dynamics in BB-LEH in relation to environmental parameters, especially salinity, could be useful in establishing a rehabilitation plan by use of "what if" scenarios. This will require laboratory determination of the effects of salinity (acclimation rather than acute effects) on hard clam respiration rate and feeding rate, since the existing hard clam bioenergetic model (Hofmann et al. 2006) requires input of these parameters and such data are not available for *M. mercenaria*, as well as field environmental data in representative habitats to allow both hindcasting and prediction of clam population dynamics. While monitoring of temperature and salinity are routinely being conducted in BB-LEH, methods of food monitoring (total Chl *a*) are inadequate and need to be re-evaluated (see above).

- High winter/spring mortalities of small seed are a recognized impediment to culture and presumably recruitment of *M. mercenaria*. The relative site-specific and seasonal growth performance and overwintering survival of different genetic stocks of juvenile hard clams, e.g., notata and unselected, "wild", needs to be evaluated. Interactions of genetic stock, environmental conditions (temperature and salinity), and nutritional status (e.g. fall and spring food quality/quantity) need to be considered.

- The densities of hard clams reported during the 2001 survey were less than ~0.7-0.8 clams m^{-2} ($\leq$ 0.074 clams ft^{-2}) over a large portion of LEH (Fig. 25), and thus at or below the density threshold that was suggested to be required for the maintenance of self-sustaining population in GSB, NY (Fig. 37). A recent NJDEP survey conducted in LEH in 2011, and in BB in 2012 (results are not included in this report) will provide updated information on bay-wide hard clam densities. Based on earlier surveys, it is thus likely that hard clam populations in BB-LEH are approaching a point where they could be recruitment limited. The spawner-recruitment relationship established for Great South Bay, NY, (Fig. 37A) needs to be assessed for the BB-LEH estuary. Limitations in productive habitat suitable for hard clams, including habitat suitable for settlement, also need to be considered.

- The increase in the estimated mortality suggests that, in addition to lower recruitment, an increased mortality rate is also reducing the population in BB-LEH, and that it may be a significant part of the reduced recruitment. The cause/s of the additional mortality remain unknown. Additional studies on this aspect are warranted.

We recommend that the above key needs for research, monitoring and management be prioritized as part of a short- and long-range strategic plan by a group knowledgeable of the hard clam resource and the BB-LEH estuary. This group should include scientists and a variety of stakeholders, including industry representatives, recreational clammers, and managers.

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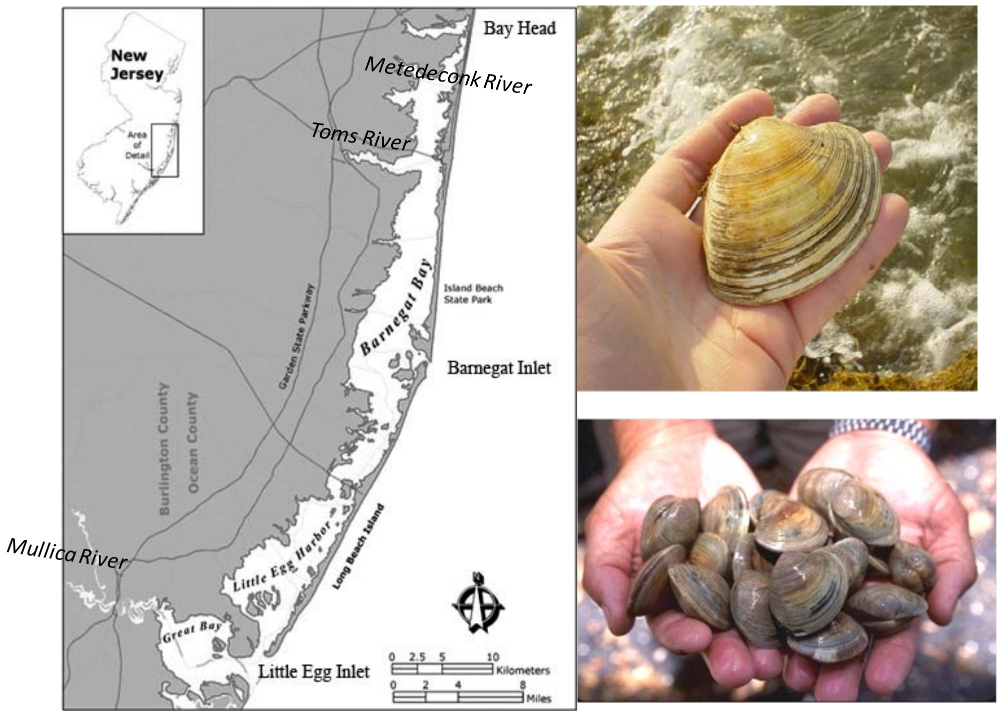
List of Figures

Figure 1: Map of the Barnegat Bay-Little Egg Harbor estuary with inset showing the location of the estuary in the State of New Jersey, and photos of adult quahogs (= hard clams), *Mercenaria mercenaria*.



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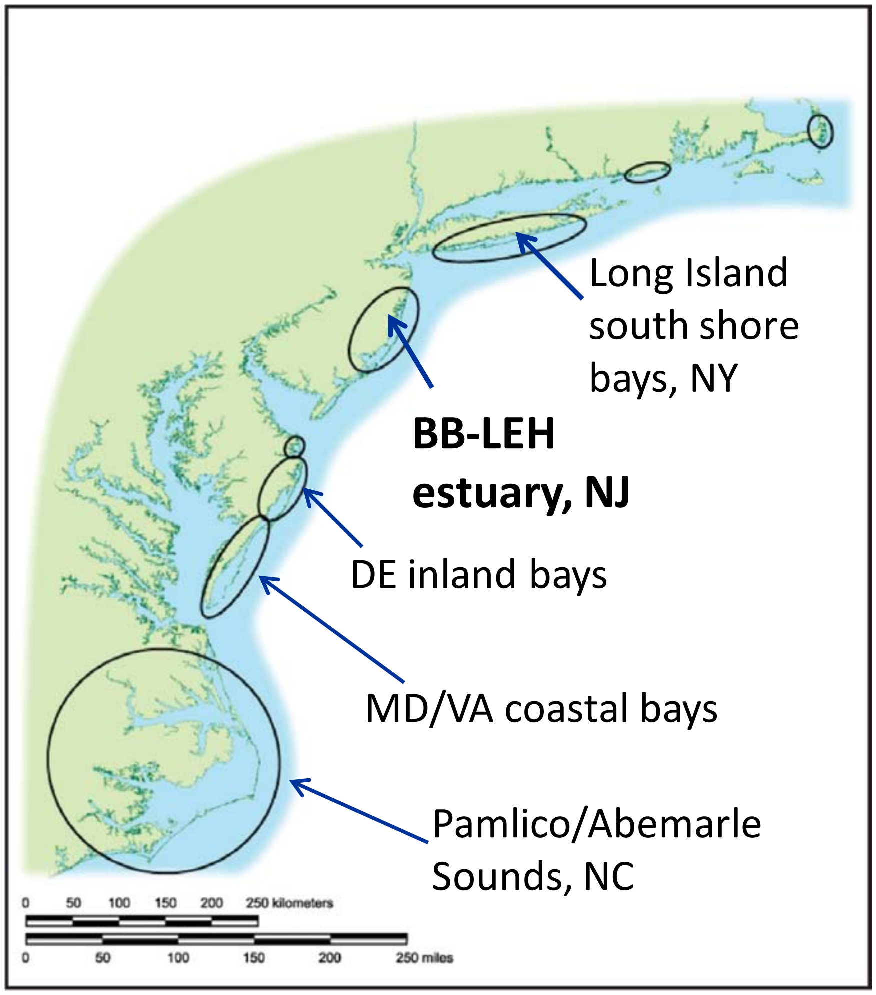

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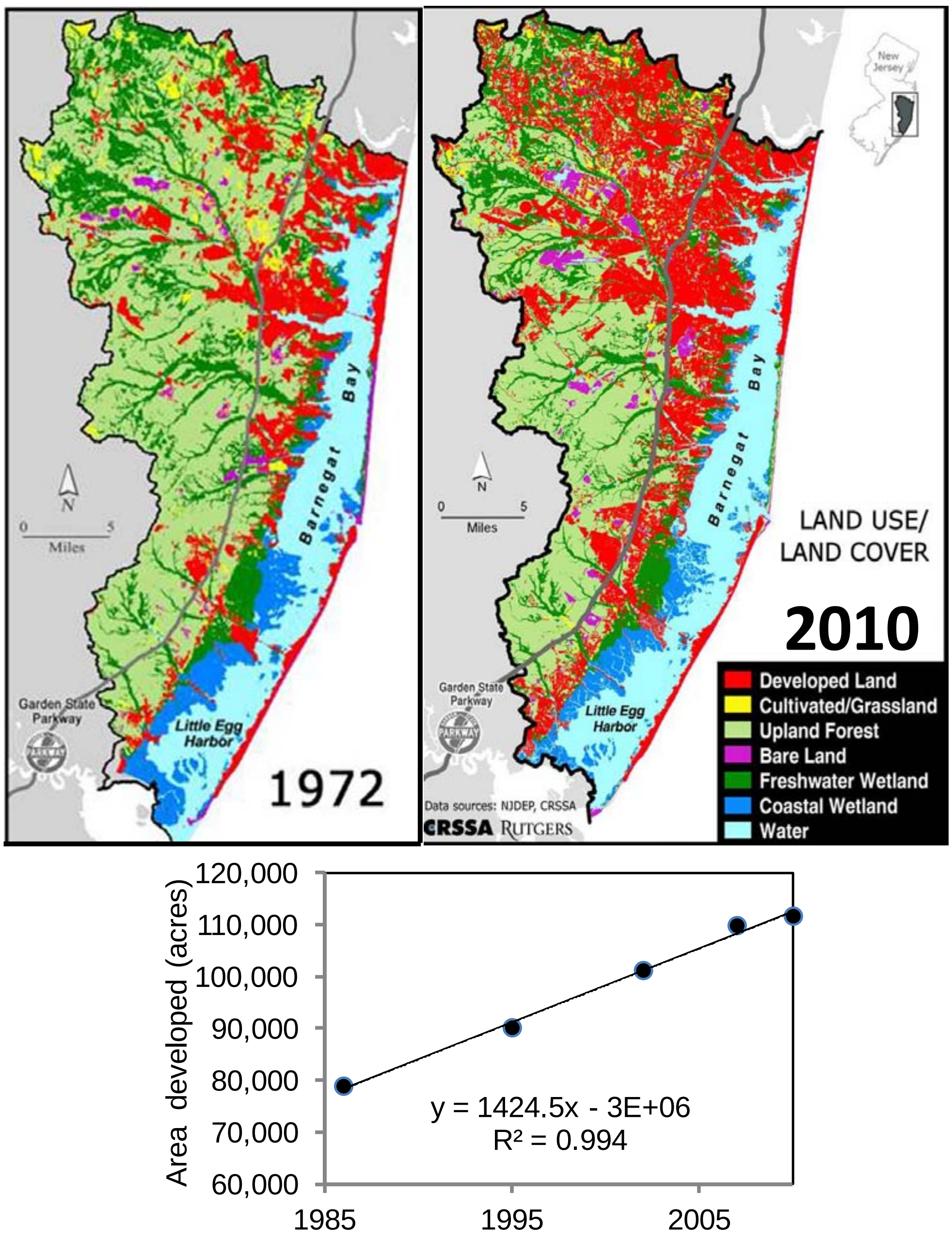

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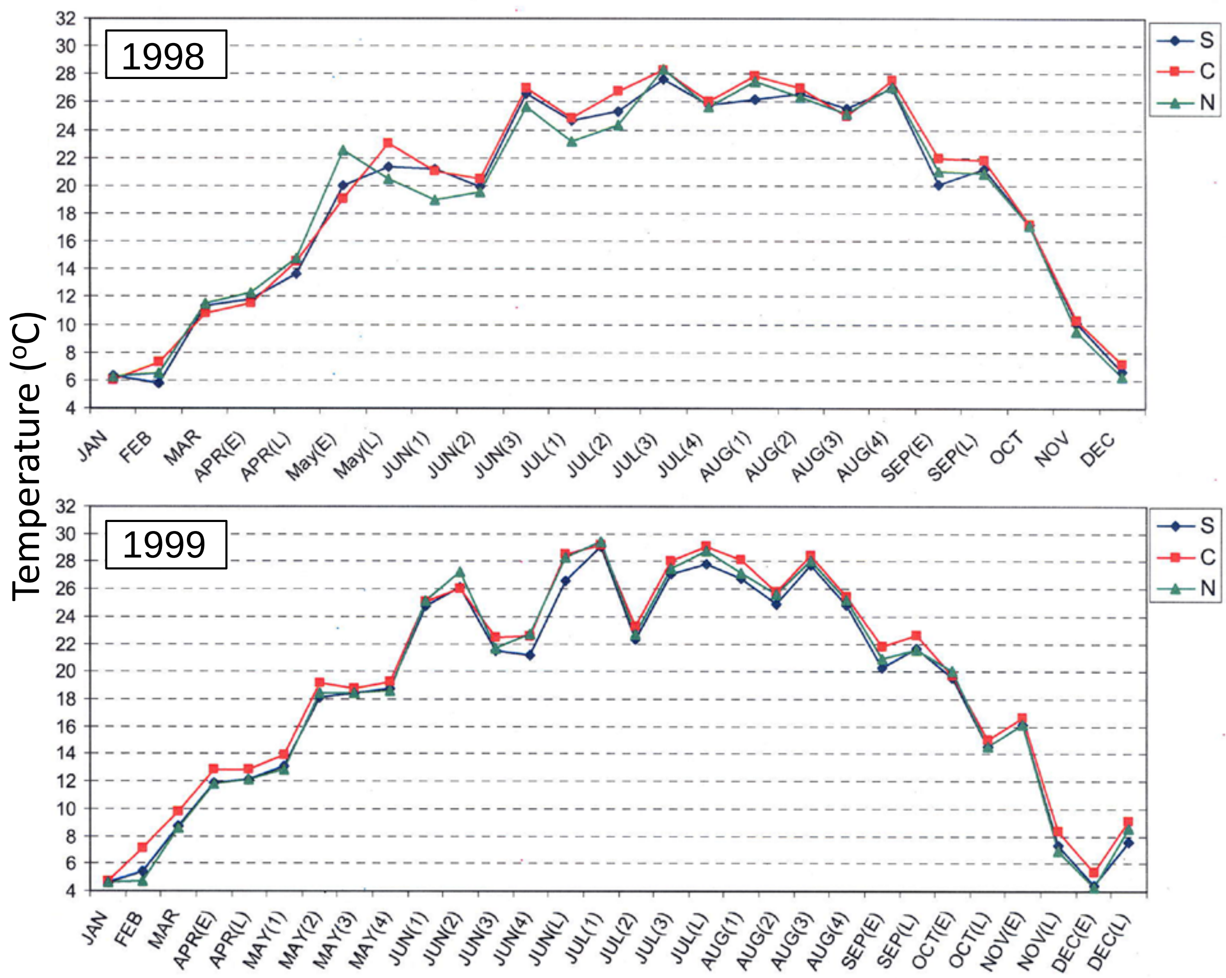

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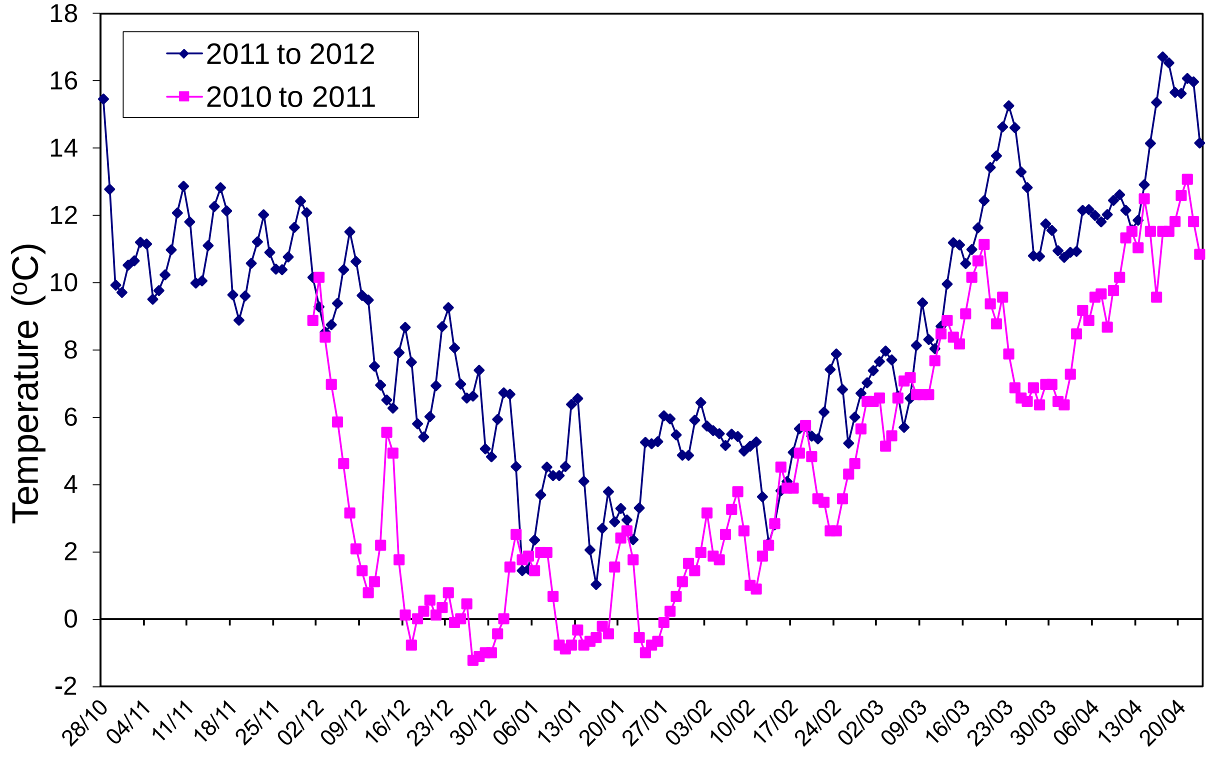

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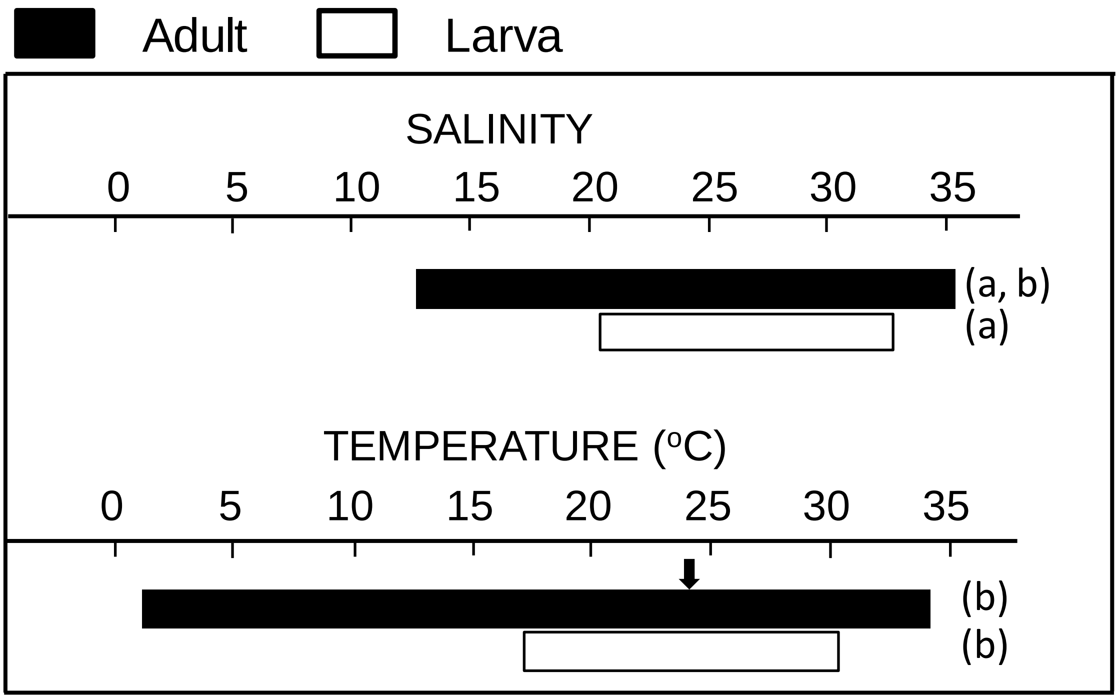

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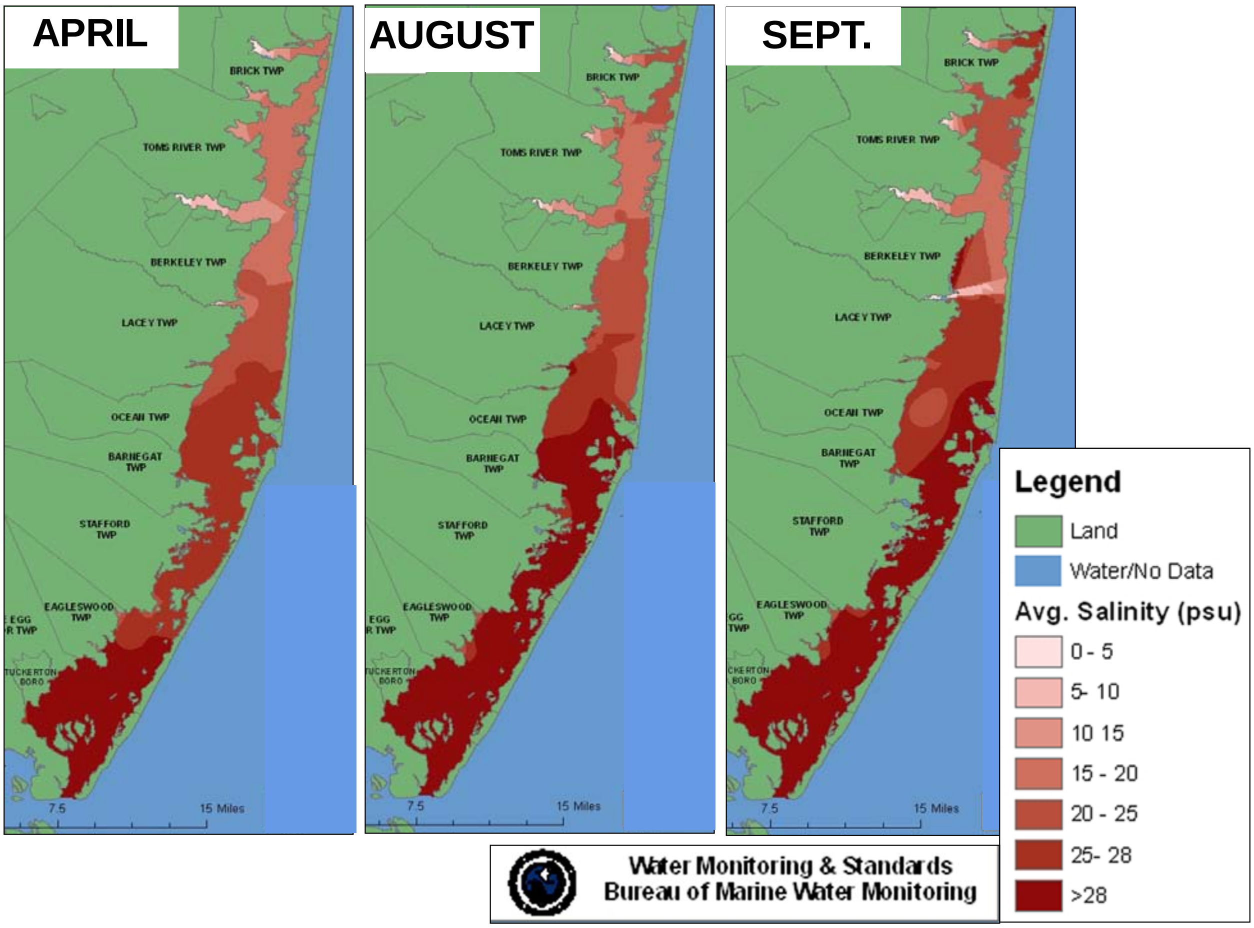

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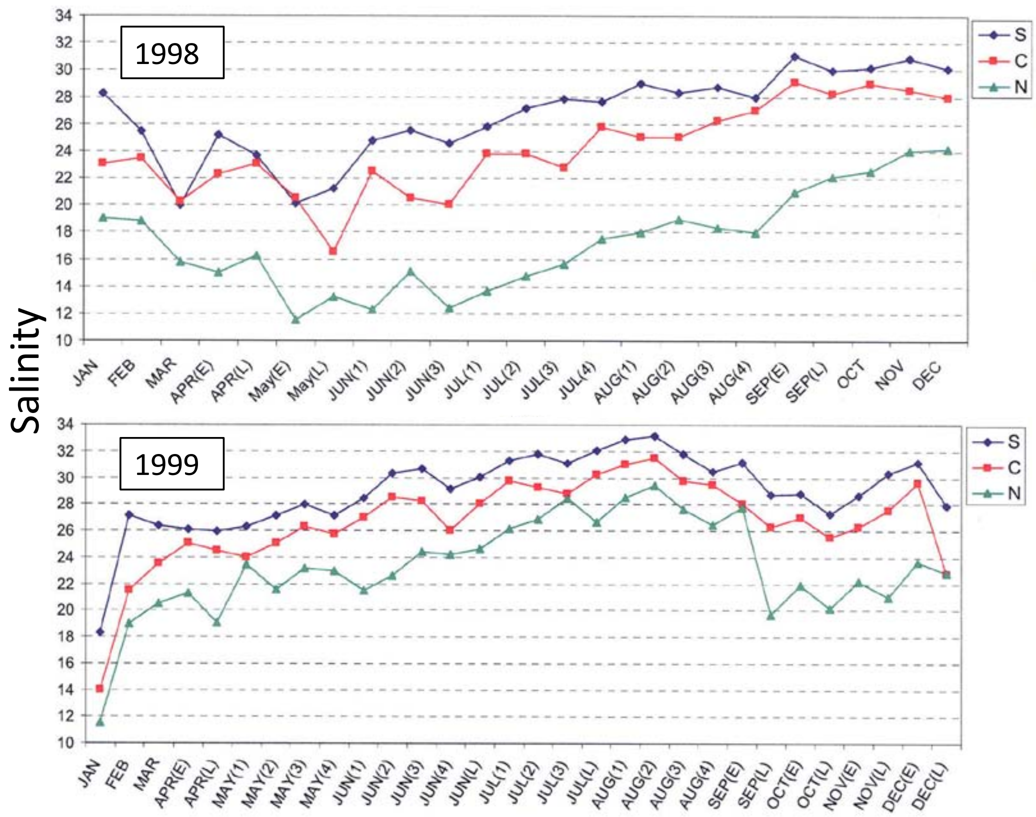

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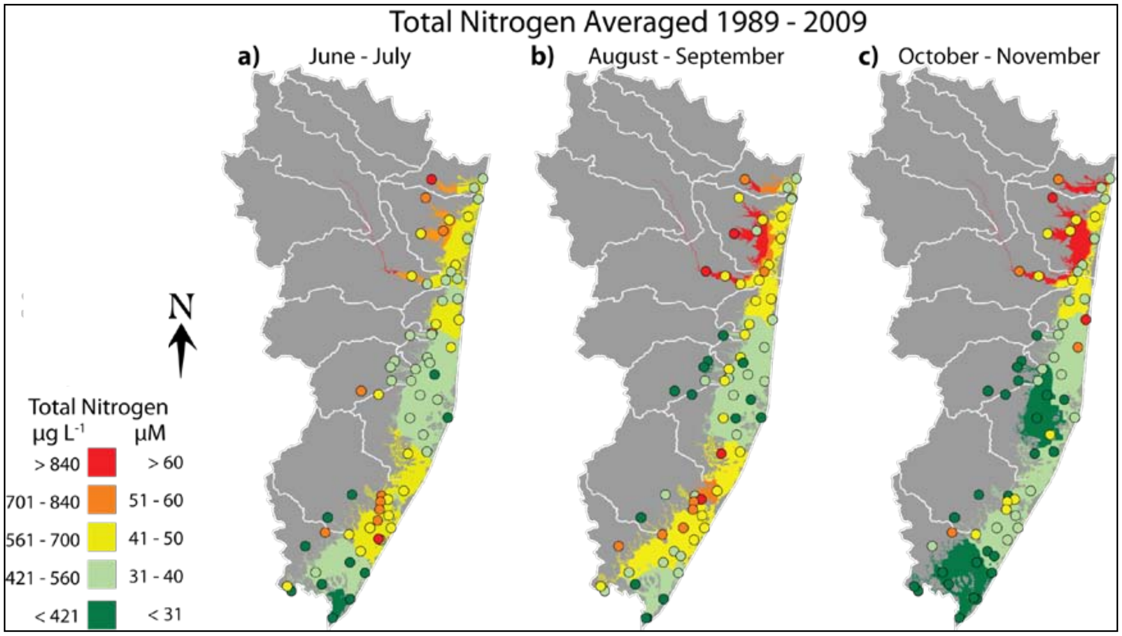

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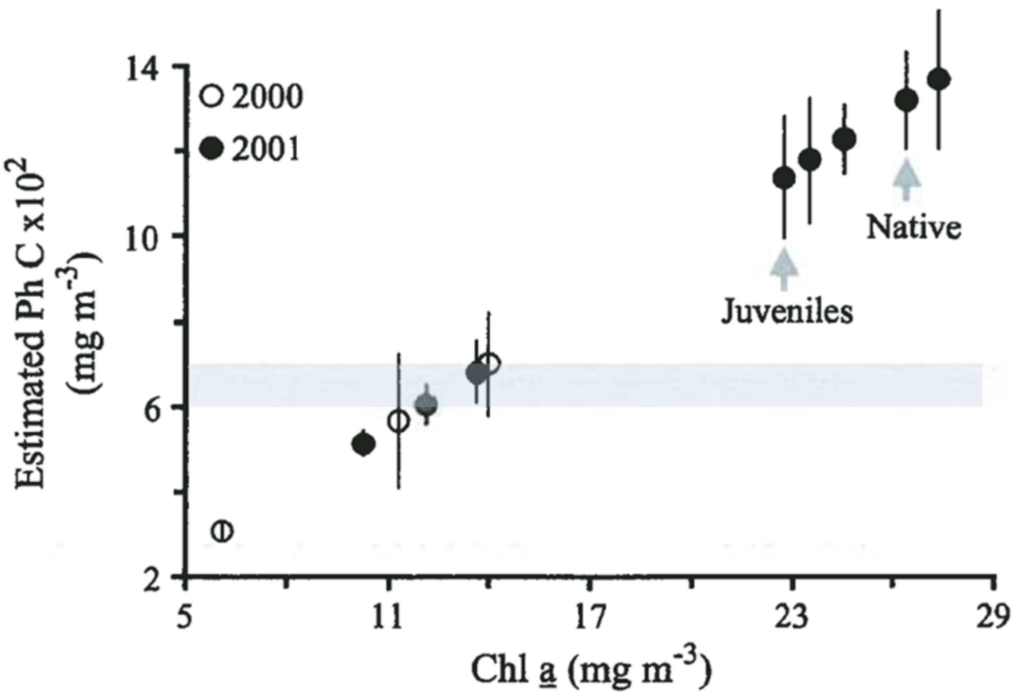

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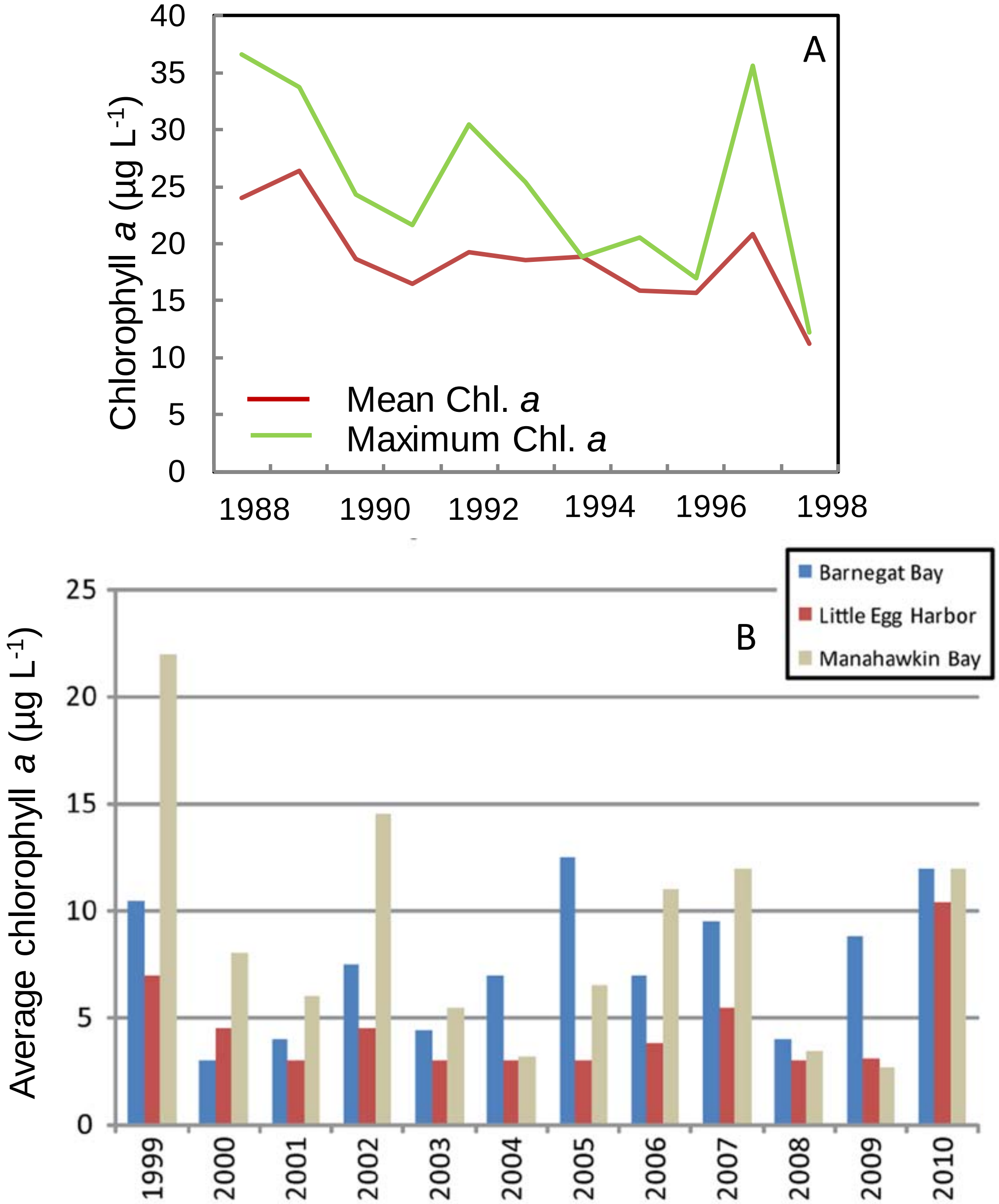

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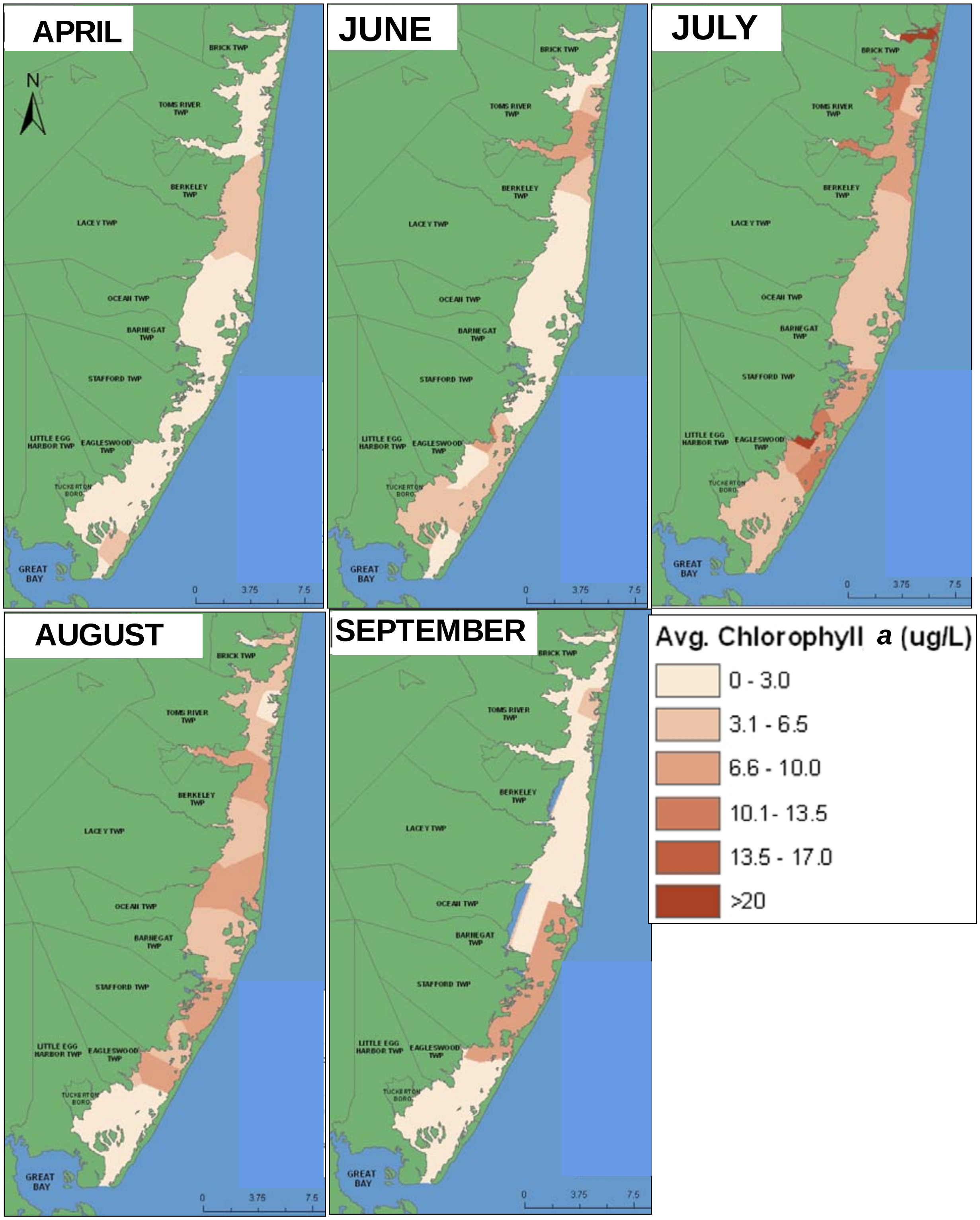

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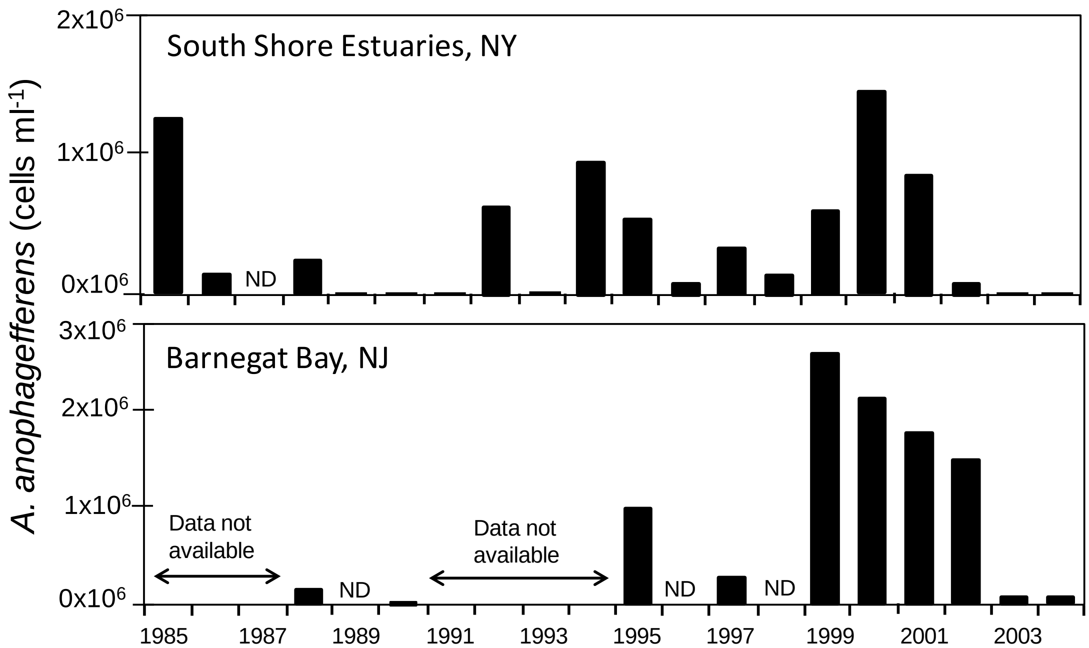

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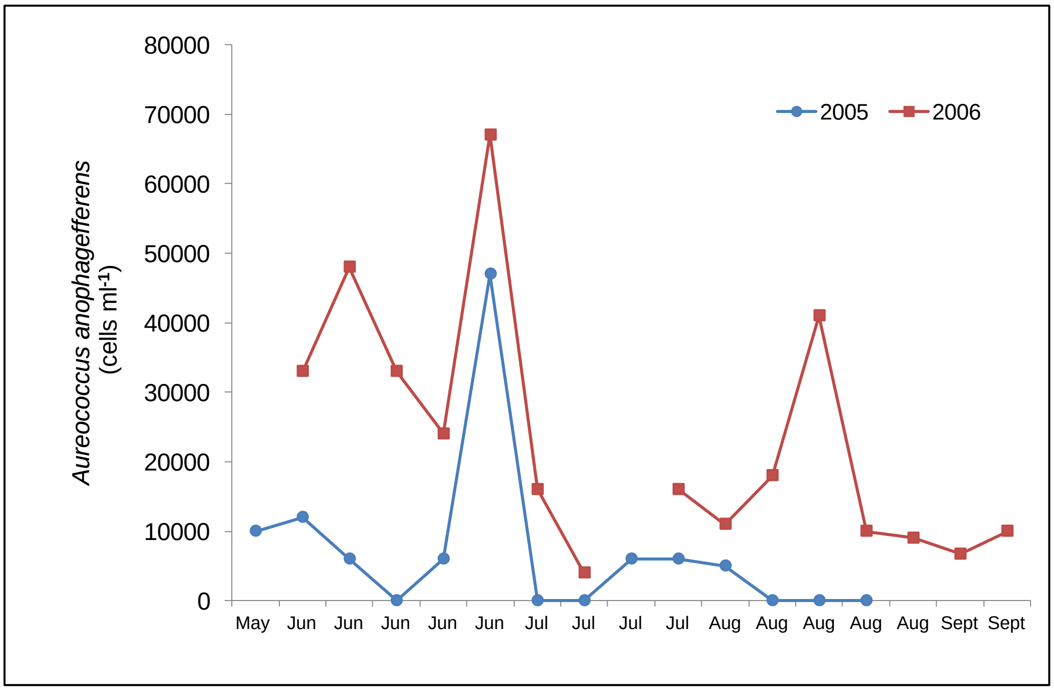

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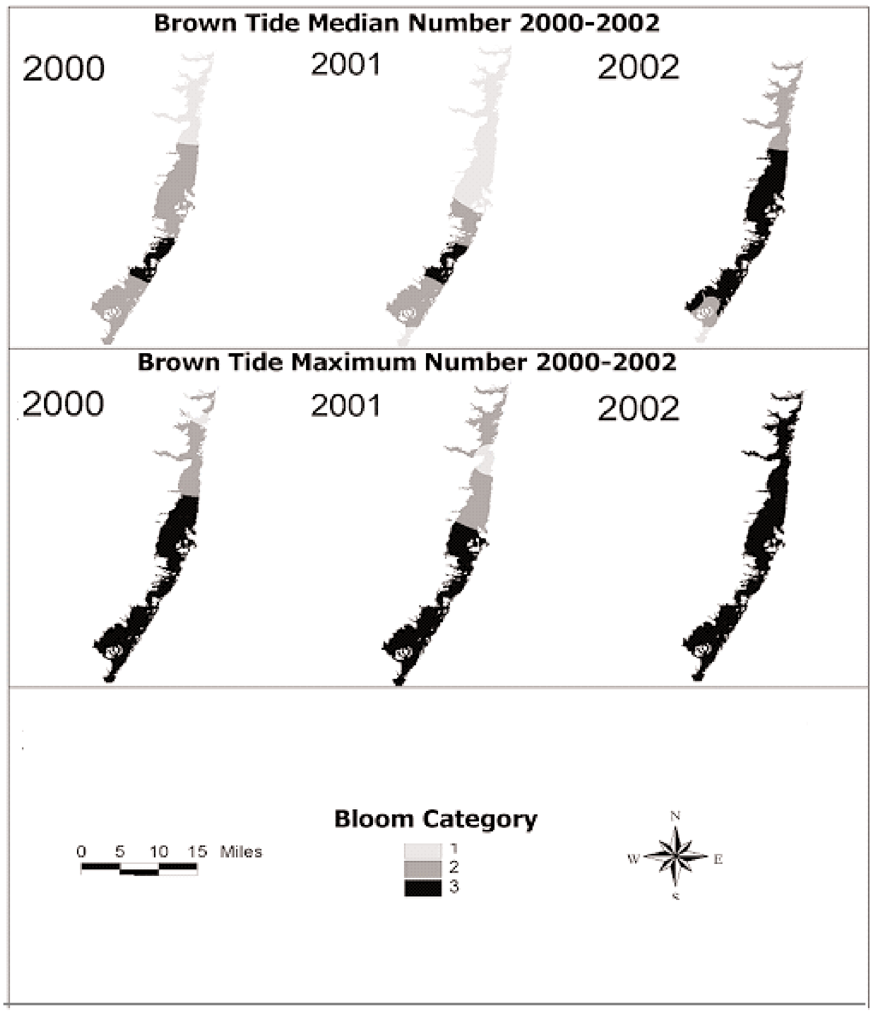
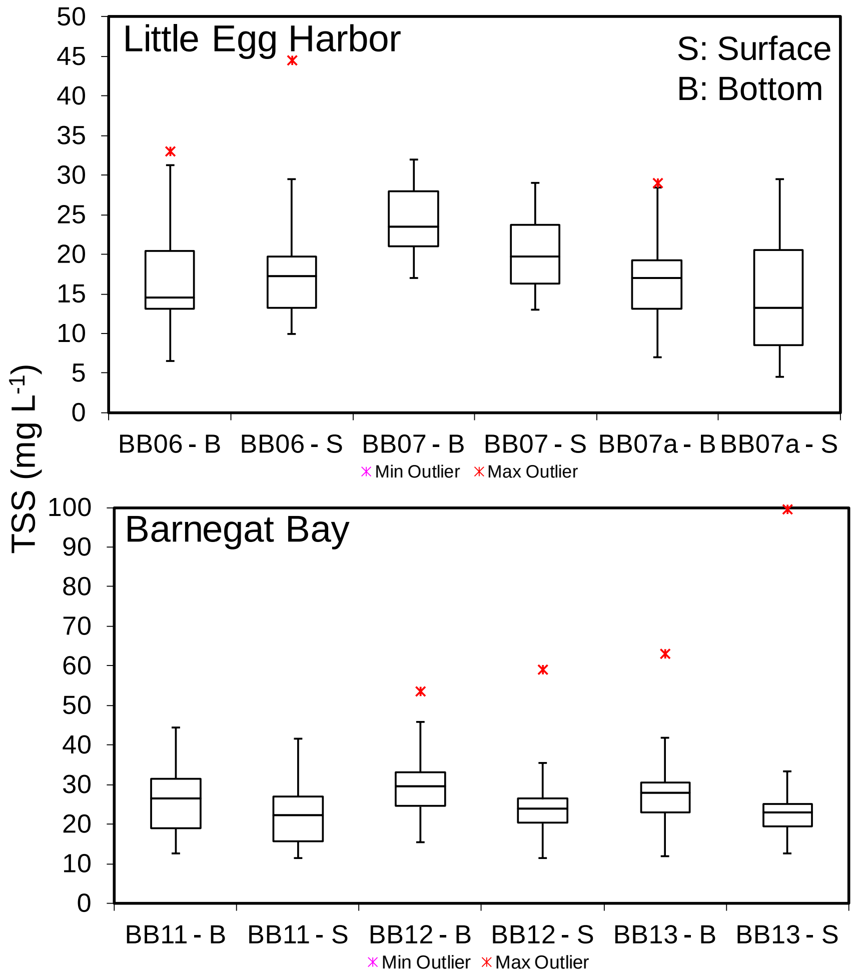


Figure 16. Box-plots showing median concentrations of total suspended solids (TSS, in mg dry weight L^{-1}) at representative locations in Little Egg Harbor and Barnegat Bay, at the surface and 30 cm off-bottom, between June-October 2011 and March to September 2012 (sampled weekly during the summer or twice a month (courtesy of Helen Pang, NJDEP Bureau of Environmental Analysis and Restoration). The length of the boxes represents 1.5*interquartile range (IQR) above the third quartile and 1.5*IQR below the first quartile.



Station	Longitude	Latitude
BB06	-74.102080	39.8526200
BB07	-74.153190	39.7926200
BB07a	-74.1571172	39.8012861
BB11	-74.235700	39.6254000
BB12	-74.268750	39.5815100
BB13	-74.324590	39.5690100

Figure 17. Characterization of bottom sediments (upper 2-5 cm) in Barnegat Bay-Little Egg Harbor, as described by mean grain size in phi (F) units (from Psuty 2004, study conducted between 1995 and 2000). Insets: mean grain size distribution in Kettle Creek and Silver Bay (a) and at the Island Beach State Park washover lobe (b), the site of the coarsest sediment at the margin of the barrier island. Categories are: silt (> 4F, < 63 µm), very fine sand (3-4F, 63 to 125 µm), fine sand (2-3F, 125 to 250 µm), medium sand (1-2F, 250 to 500 µm), coarse sand (0-1 F = 500 µm to 1 mm), and very coarse sand and greater (< 0F) based on the Wentworth scale.

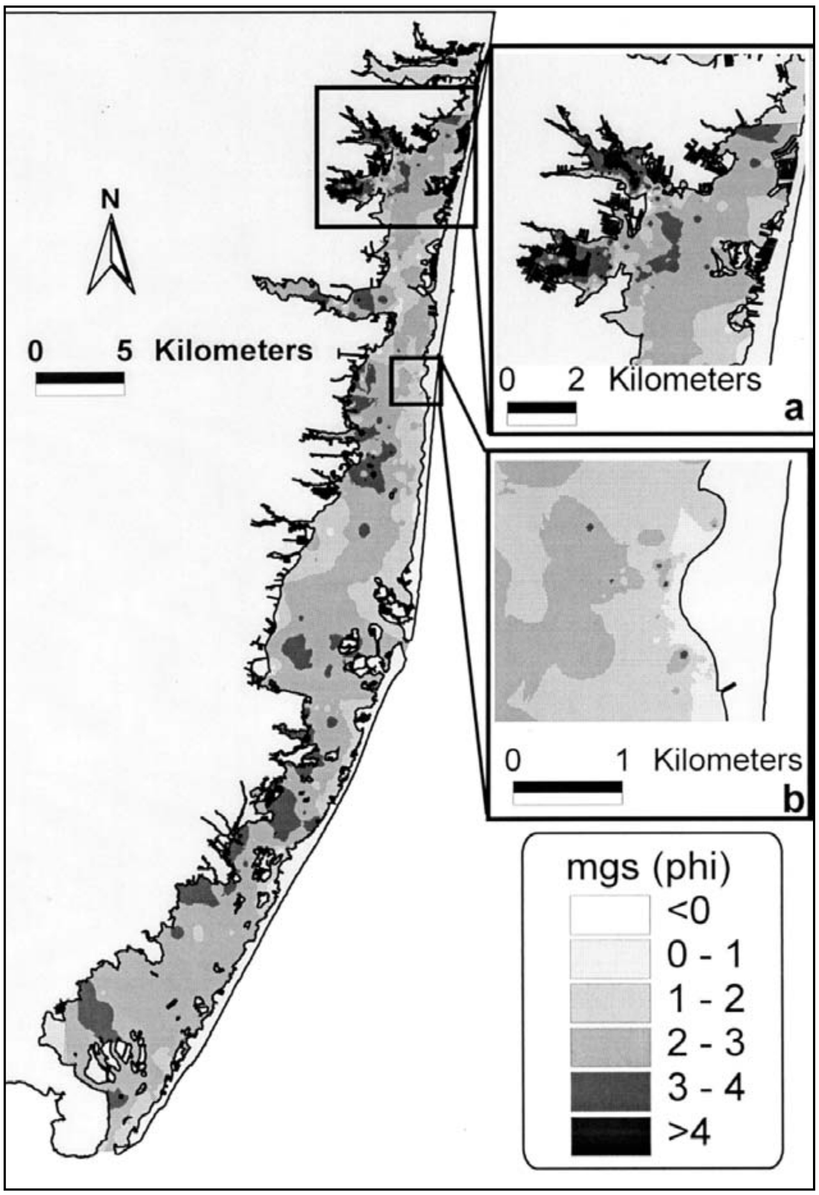


Figure 18. Eelgrass (*Zostera marina*) distribution and percent cover in the Barnegat Bay-Little Egg Harbor Estuary and Great Bay. Inset marks location of the three bays on the New Jersey coast.

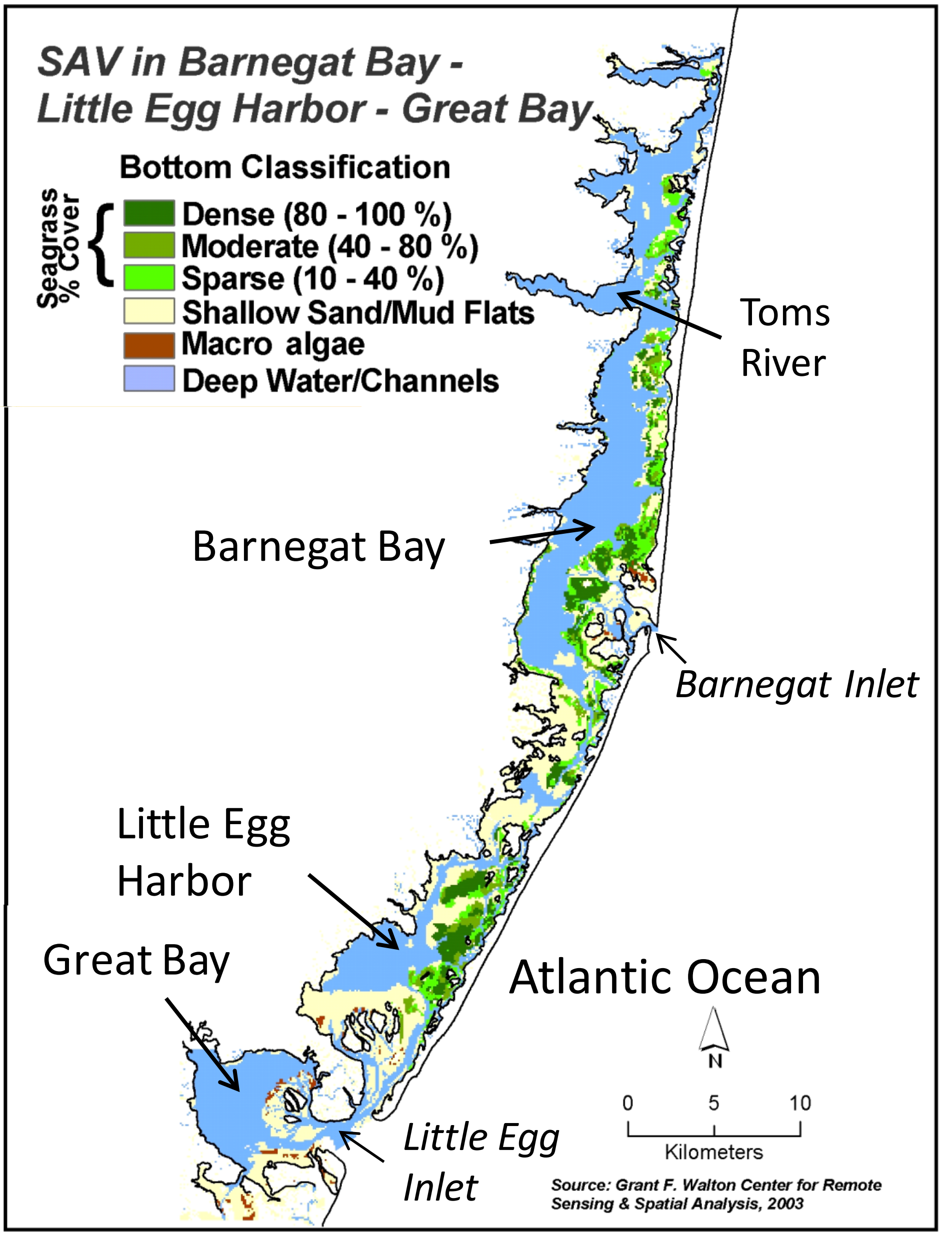


Figure 19. Map showing the location on uncertified waters due to bacterial coliform levels in the BB-LEH estuary in 2012 (source: NJDEP website: http://www.state.nj.us/dep/wms/bmw/waterclass.htm)
. A = approved waters; P = prohibited; S = seasonal (November to April); SJ = seasonal (January to April); SR = Special Restricted.

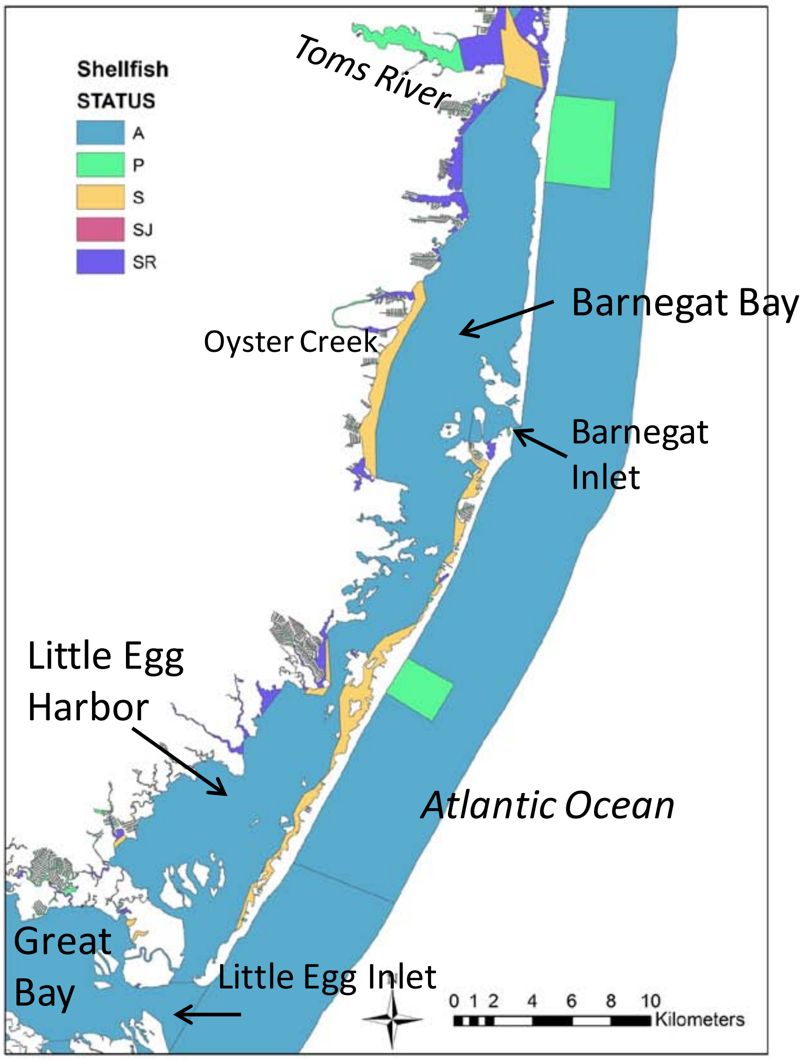


Figure 20. Hard clam landings at Parsons Seafood, Tuckerton, NJ, which according to Carriker (1961) represent ~10% of the clams harvested from Little Egg Harbor, between 1929 and 1977. Data from Carriker (1961) plus additional data provided by the same clam buyer and reported by Kraeuter et al. (1996); data are missing for 1970.

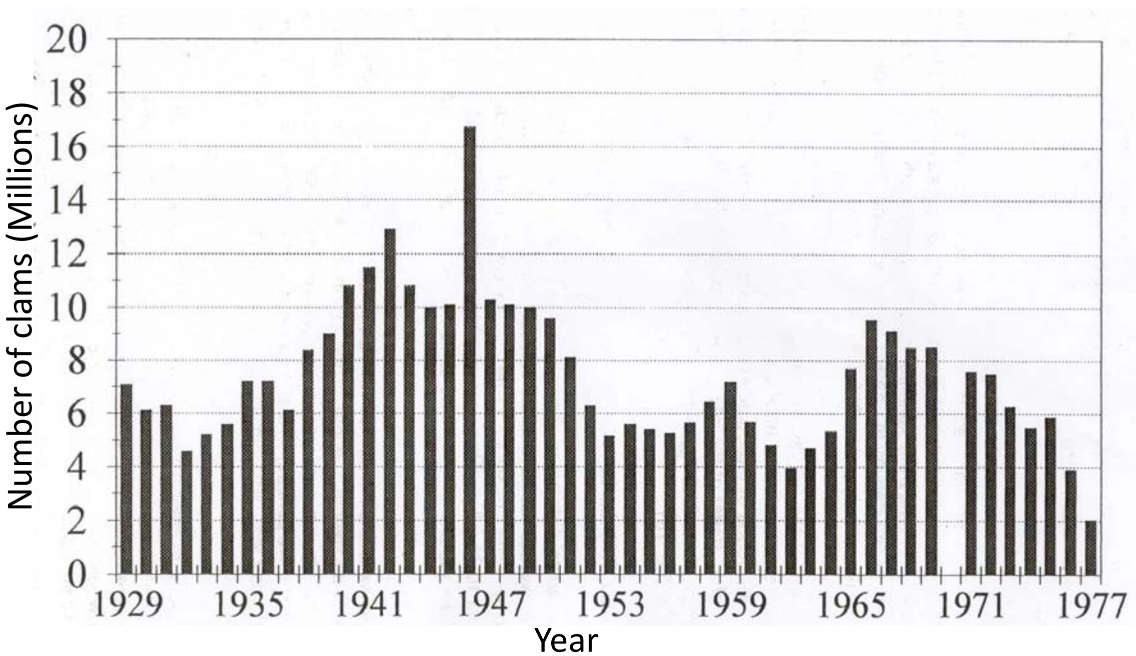


Figure 21: Hard clam landings A) for Ocean County from 1960-2005 (National Marine Fisheries Service data), and human population in Ocean County between 1900 and 2006 (plots from G. Calvo, NJDEP). Landings data unavailable for 2001 and 2003.

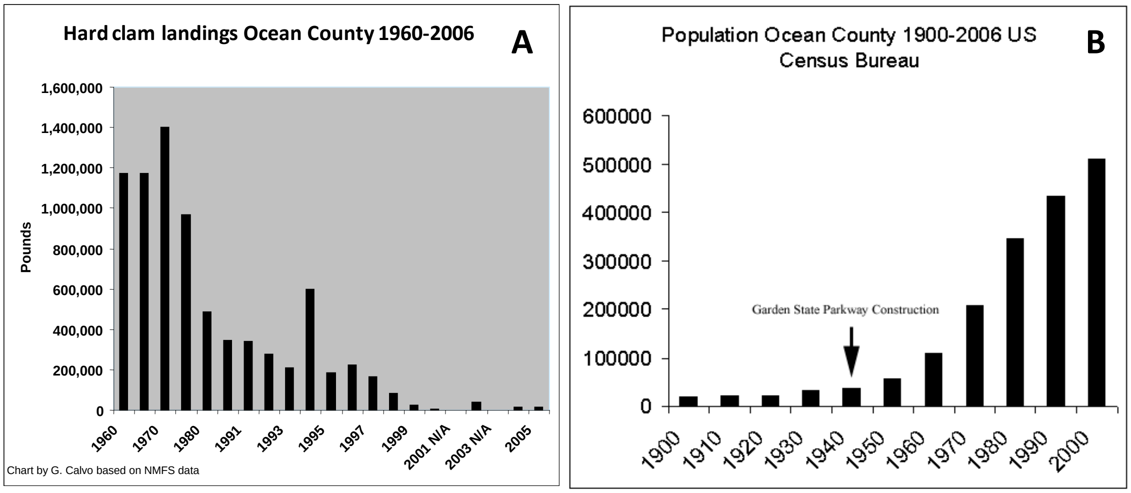


Figure 22. Number of recreational (A), including both NJ residents and non-residents, and commercial “clamming” licenses (B) sold at the NMFS Nacote Office, Atlantic County, for harvesting in the State of New Jersey between 1980 and 2012 (data provided by Gustavo Calvo, NJDEP Division of Fish and Wildlife). License costs = $50 for a commercial license; $10 and $20 for adult residents and non-residents respectively. Note that commercial licenses include clammers that were once involved in relaying activities, and worked for depuration plants in Monmouth County, in addition to commercial clammers and aquaculturists. Since 2008 the licenses are not specific for clamming, but are required for harvesting of all species of benthic molluscs except conchs (www.state.nj.us/dep/fgw/marinelicenses.htm).

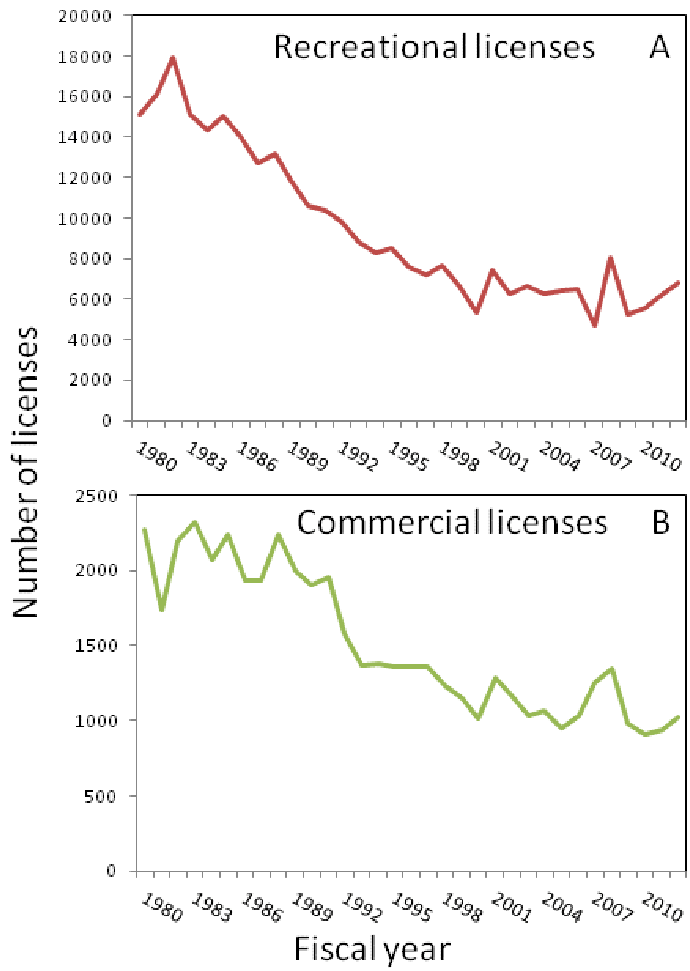


Figure 23. Hard clam landings in Great South Bay, NY, with location map showing Long Island south shore estuaries.

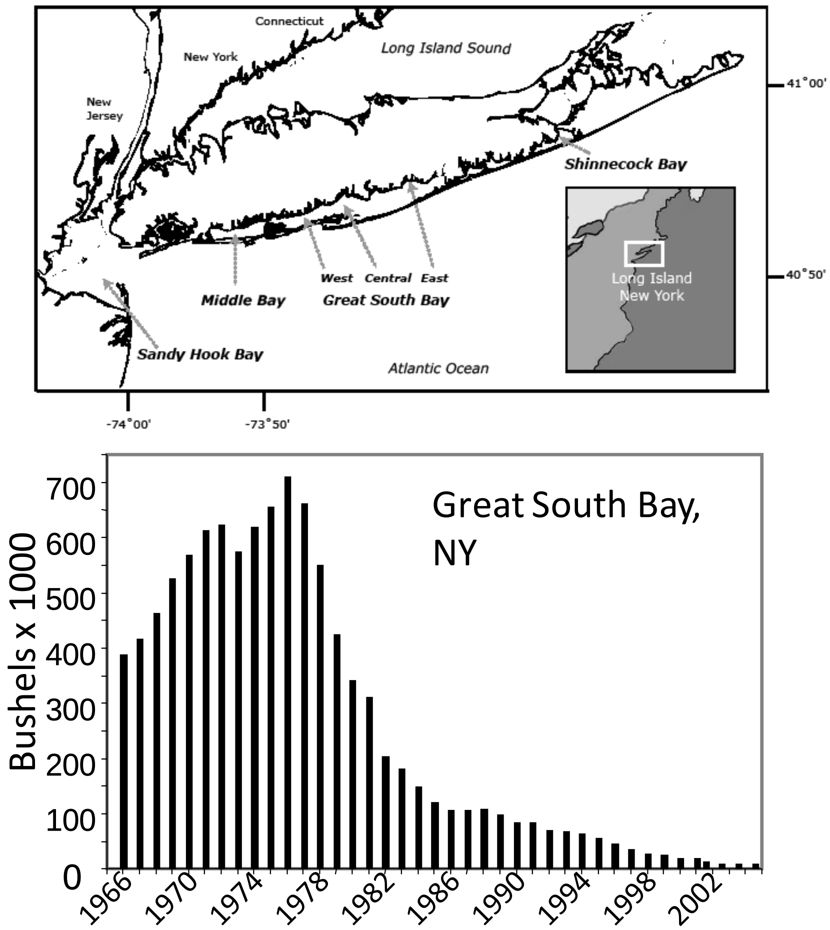
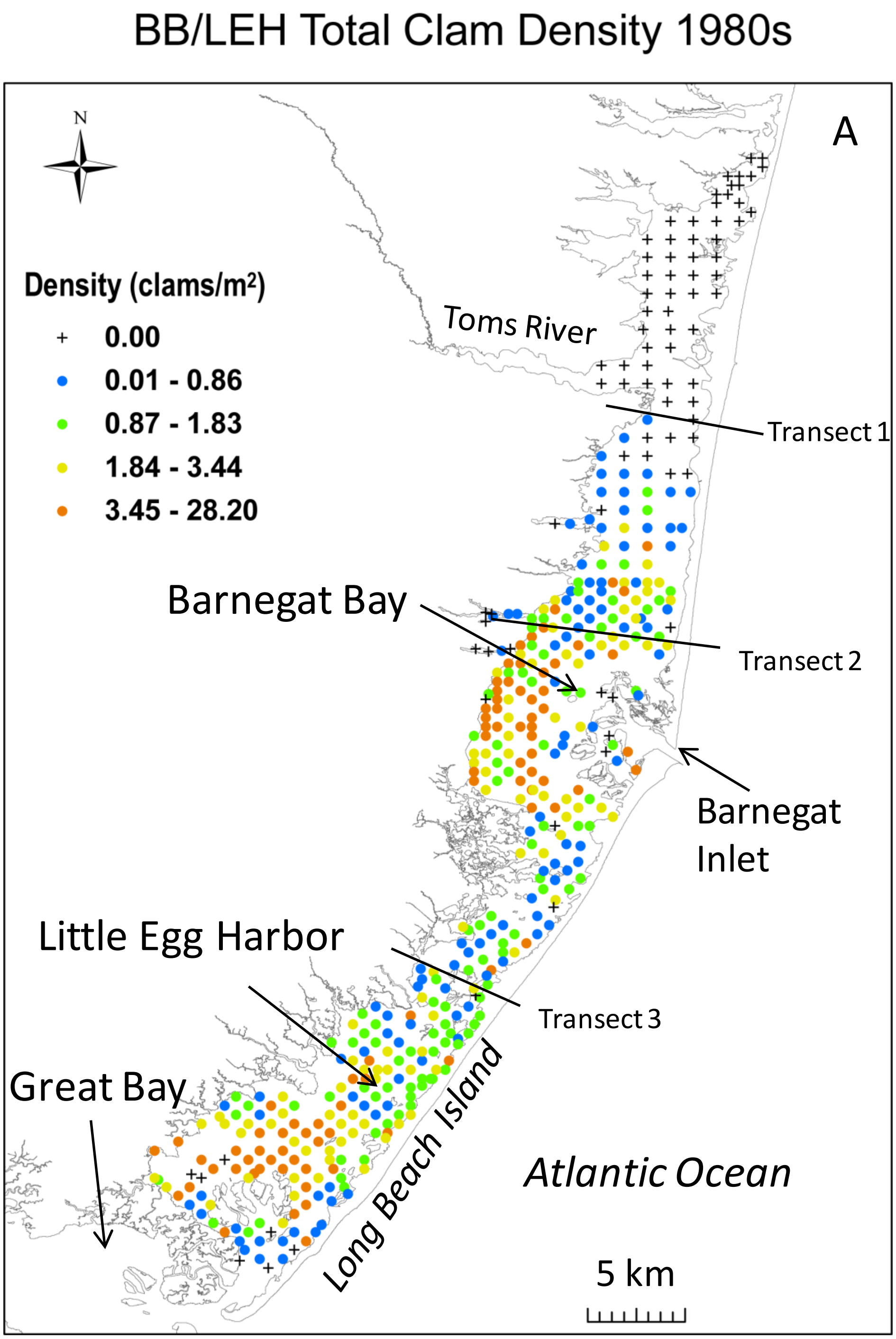


Figure 24. Map showing the total abundance (clams m^{-2}) of *Mercenaria mercenaria* (including all size classes collected) from surveys conducted by the Bureau of Shellfisheries in the mid-1980s in **A)** Barnegat Bay and Little Egg Harbor, (clam density intervals in clams ft^{-2} = 0.9x10^{-3} - 0.080; 0.081 - 0.170; 0.171 - 0.320; 0.321 - 2.620), and **B)** Great Bay, NJ [maximum density interval = 0.321 – 1.940 clams ft^{-2})]. Clam density intervals were based on a quantile classification scheme which provides a more even distribution of values among various intervals.



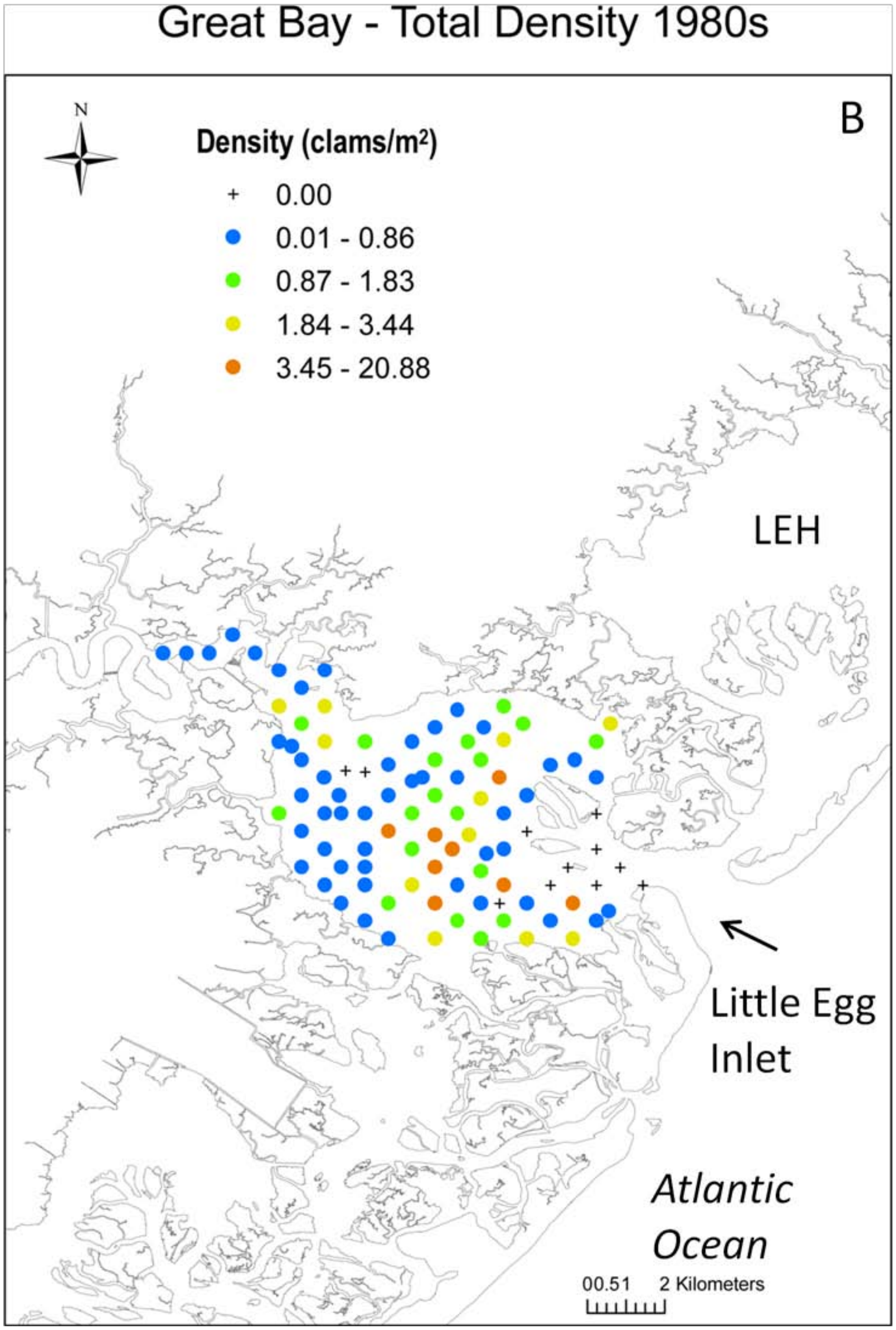

Great Bay - Total Density 1980s
B
N
Density (clams/m2)
0.00
0.01 - 0.86
0.87 - 1.83
1.84 - 3.44
3.45 - 20.88
LEH
Little Egg
Inlet
Atlantic
Ocean
00.51 2 Kilometers

Figure 25. Map of Little Egg Harbor comparing the total abundance (clams m^{-2}) of *Mercenaria mercenaria* during the mid-1980s survey (density intervals as in Fig. 24) and that conducted in 2001 [maximum density interval: 3.45 – 8.08 clams m^{-2} (= 0.321 – 0.751 clams ft^{-2})] .

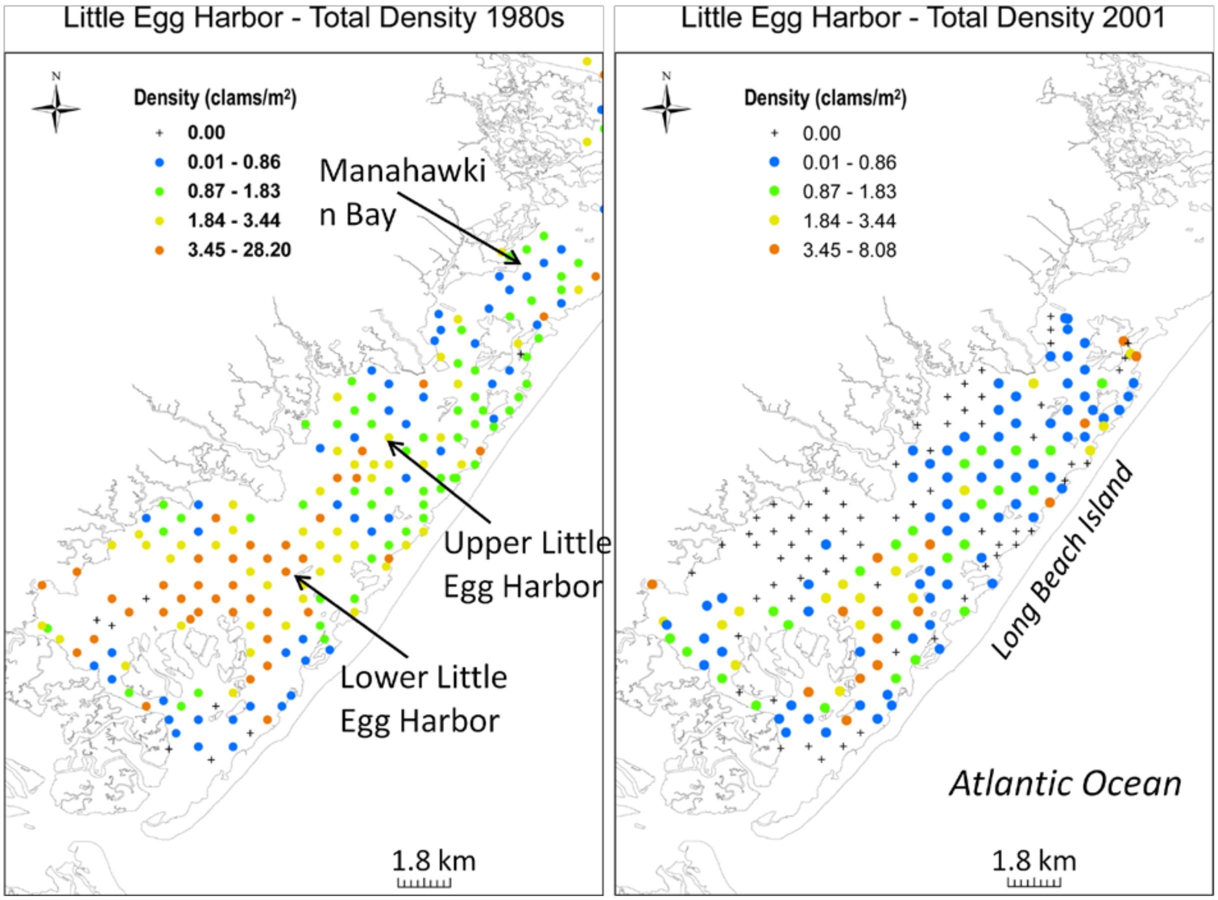


Figure 26. Map showing the abundance of chowder clams (>76 mm SL) (in # m^{-2}) of *Mercenaria mercenaria* from surveys conducted by the Bureau of Shellfisheries in the mid-1980s in Barnegat Bay-Little Egg Harbor. Density intervals in clams ft^{-2} = $0.9x10^{-3}$ – 0.020; 0.021 – 0.042; 0.043 – 0.110; 0.111 – 1.198.

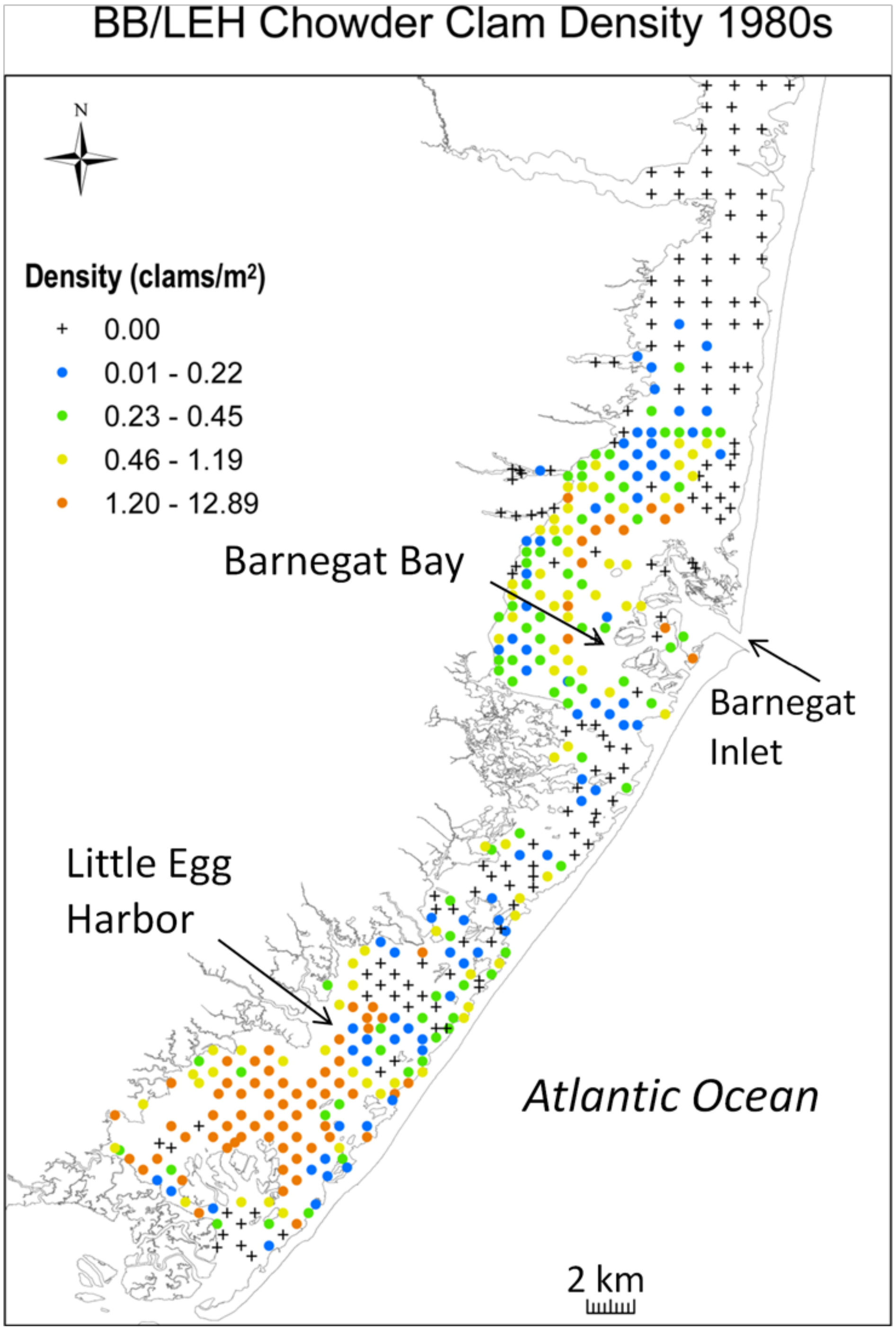


Figure 27. Map of Little Egg Harbor comparing the abundance of chowder clams (number m^{-2}) of *Mercenaria mercenaria* during the mid-1980s survey (clam density intervals as in Fig. 24) and that conducted in 2001 (maximum density interval: 1.20 – 7.59 clams m^{-2} (= 0.111 – 0.705 clams ft^{-2}).

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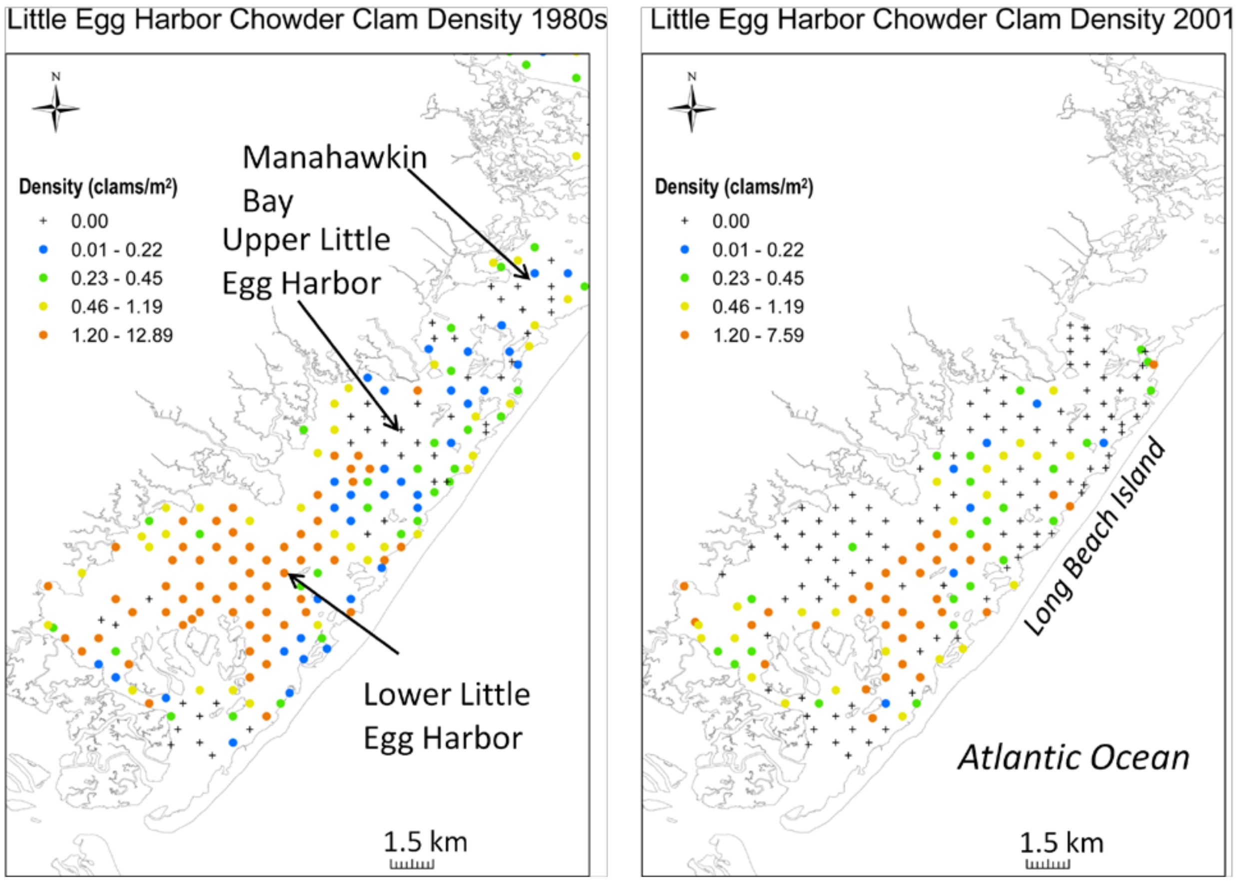


Figure 28. Densities of sublegal-sized clams during the 1980s survey conducted in the 1980s in LEH. Note that densities of sublegal-sized clams (30 to 37 mm SL) dropped to 0.12 to 0.48 clams m^{-2} (0.01 to 0.04 clams ft^{-2}) at the few sites (n = 8 out of 189) where they occurred during the 2001 survey, suggesting recruitment limitation.

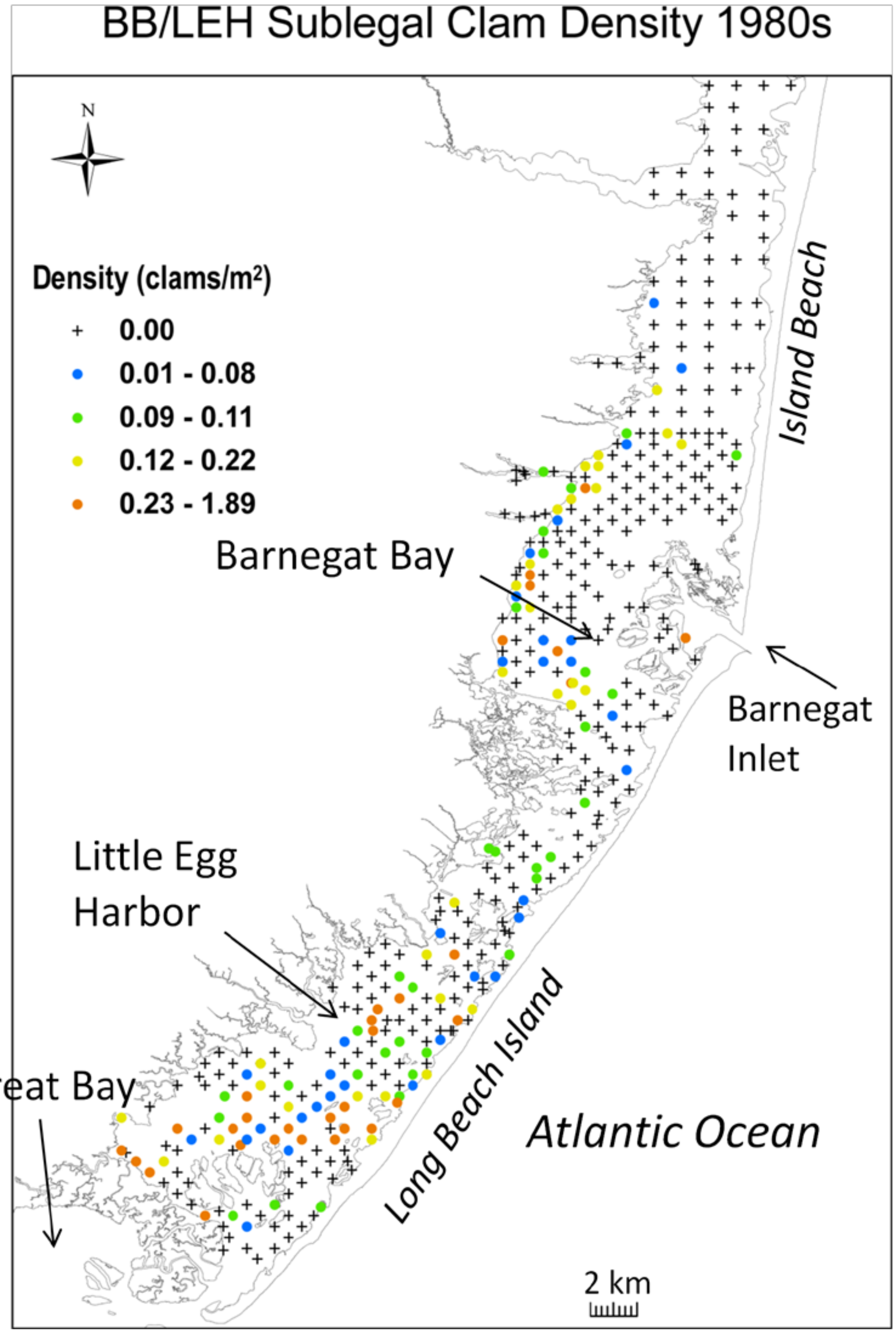


Figure 29. Mean population size structure (± standard error, SE) of *Mercenaria mercenaria*, based on all commercial size classes, defined below from surveys conducted in the mid-1980s in Little Egg Harbor (LEH) (n = 184 sampling stations), Barnegat Bay (BB) (n = 228 stations), and Great Bay (GB) (n = 93 stations). Sublegal clams, 30 to 37 mm SL; Littleneck clams, 38-55 mm SL; Cherrystone clams, 56-76 mm SL; Chowders, > 76 mm SL.

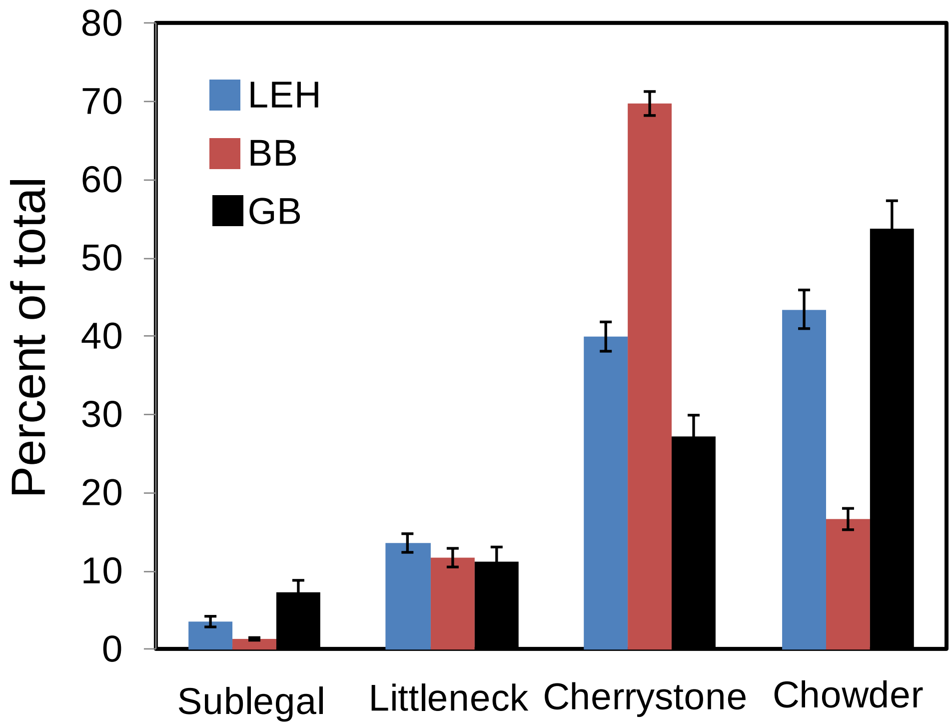


Figure 30. Comparison of the population size structure (± standard error, SE) of *Mercenaria mercenaria*, based on mean percentage of each size class, defined as in Fig. 26, from surveys conducted in the mid-1980s in northern BB, from transect 1 south of Toms River to transect 2 at Forked River, and lower section of BB including Manahawkin Bay, transect 2 from Forked River to Route 72 (transect 3) (transects shown in Fig. 24).

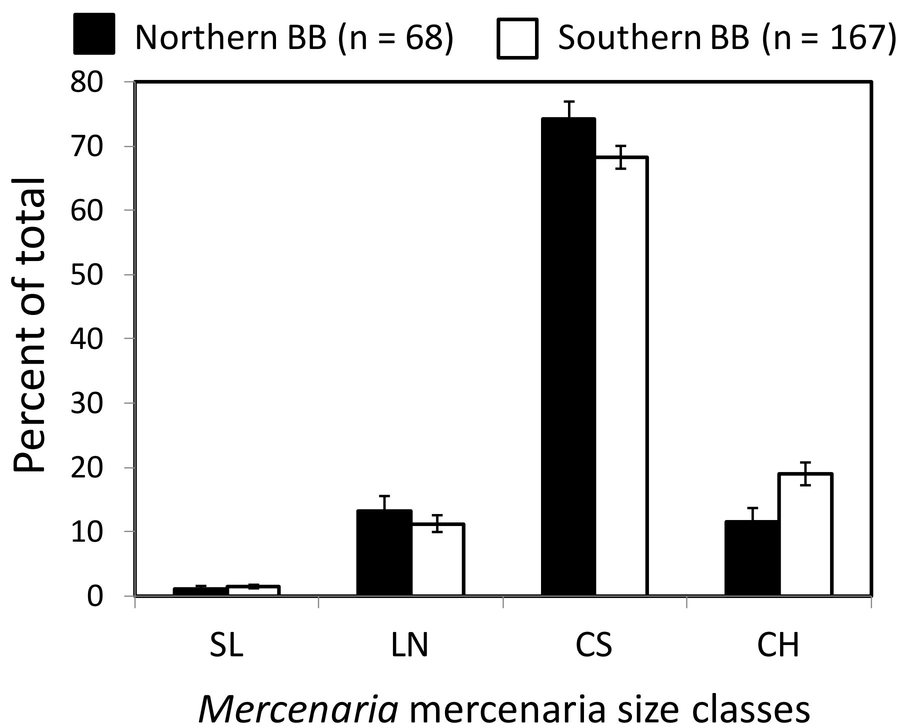


Figure 31. Comparison of the population size structure of *Mercenaria mercenaria* in Little Egg Harbor in the mid-1980s and in 2001 (mean ± SE), based on commercial size classes, as defined in Fig. 29.

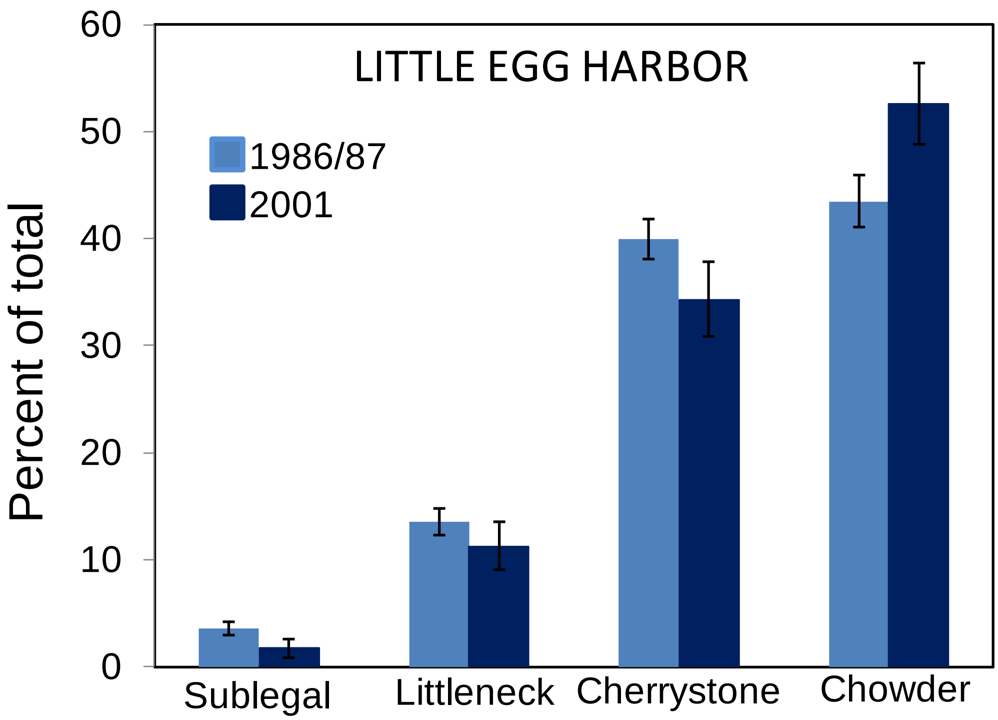


Figure 32. Temporal patterns of abundance for all stages of hard clam larvae in Little Egg Harbor in four successive summers (data from Carriker 1961, plotted in Fegley 2001). Note the difference in timing of larval presence, the variable levels of abundance and the remarkably high larval densities observed in 1951. The upper Fig. (a) is repeated with the values logged (b) to allow comparison of larval densities among years.

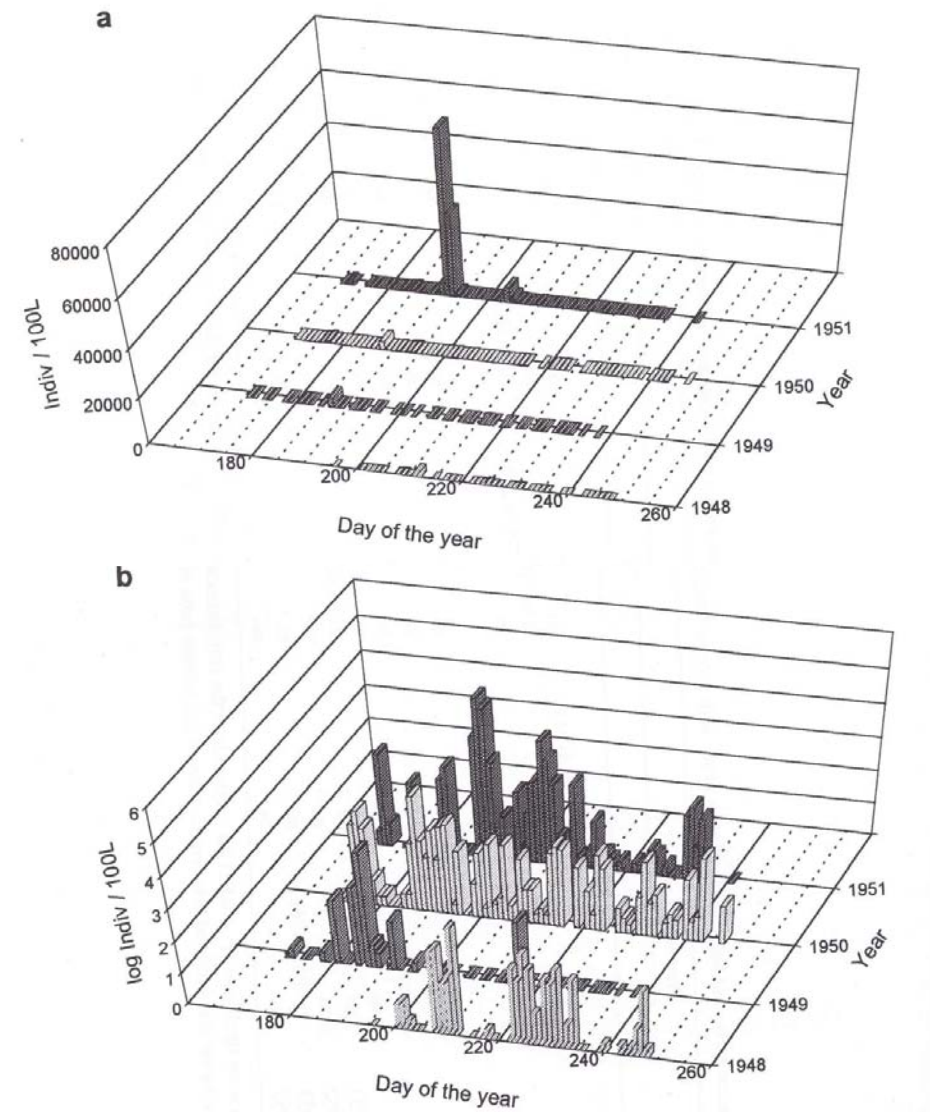


Figure 33. Hard clam cohort survival in the Shark River, NJ (plotted from data by Connell, 1983, and fitted to a power curve).

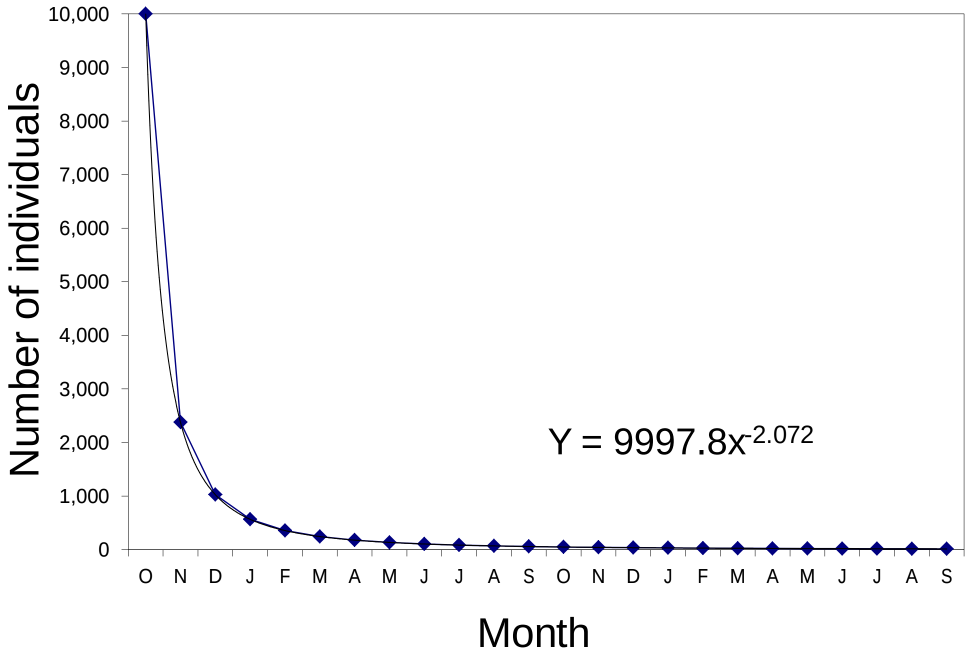


Figure 34. Average shell length of juvenile hard clams collected in the Shark River, NJ, and tracked over a year (Oct. 1979 to Oct. 1980) (data plotted from Connell 1983; dotted line indicates that no data were available in July) (see text).

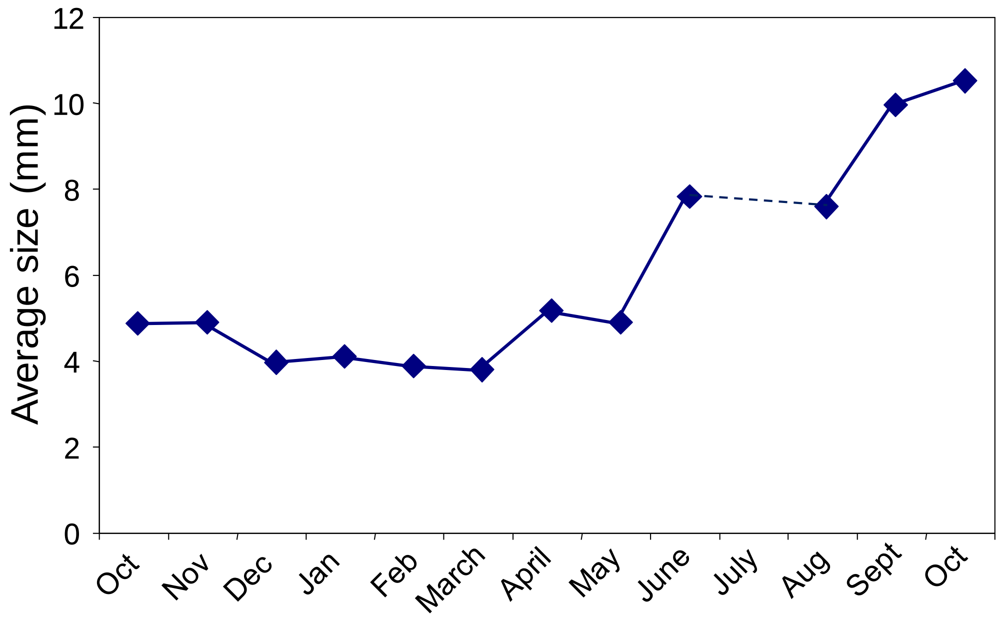


Figure 35. Survivors based on direct measurement data and life table from Connell (1983) and size-at-age shell structure analysis for dead individuals collected in Barnegat Bay, NJ (Kennish, 1978). Kennish data are a mean of 4 stations and normalized to an initial group of 5.8 individuals to make the curve comparable with that of Connell.

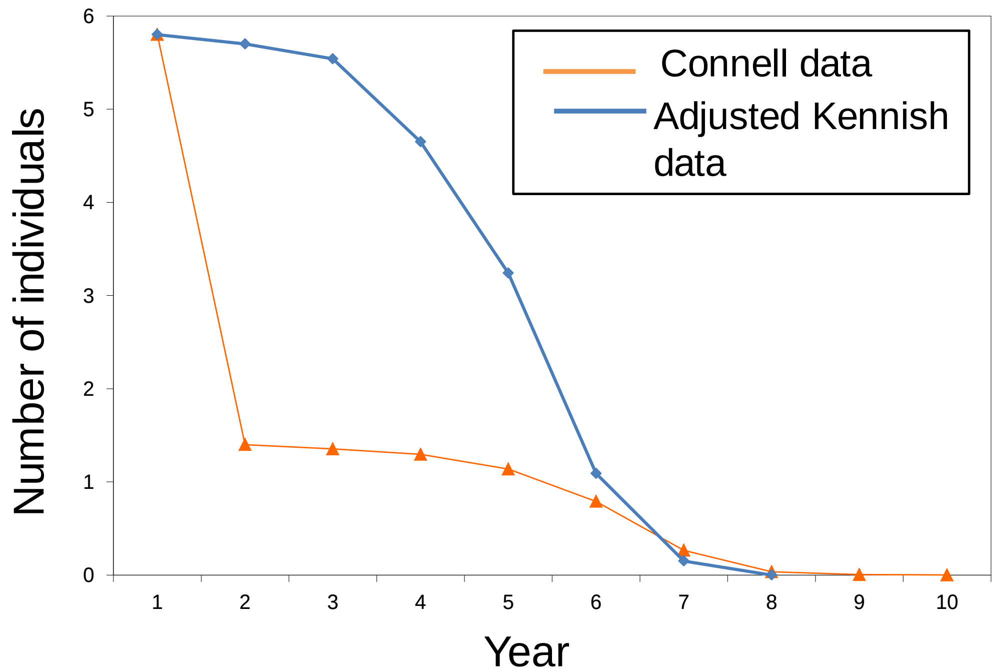


Figure 36. A. Quarterly numbers of recruiting hard clams m^{-2} at three sites in Absecon Bay, NJ The sites were on or near the dredge spoil pile that parallels the channel from Absecon Creek to Absecon Channel (Markers Flasher-F-11 to Flasher-F-9) (data plotted from Durand and Gabry 1984); **B.** annual variation in clam recruitment (mean ± SD, re-plotted based on same data as above, see text).

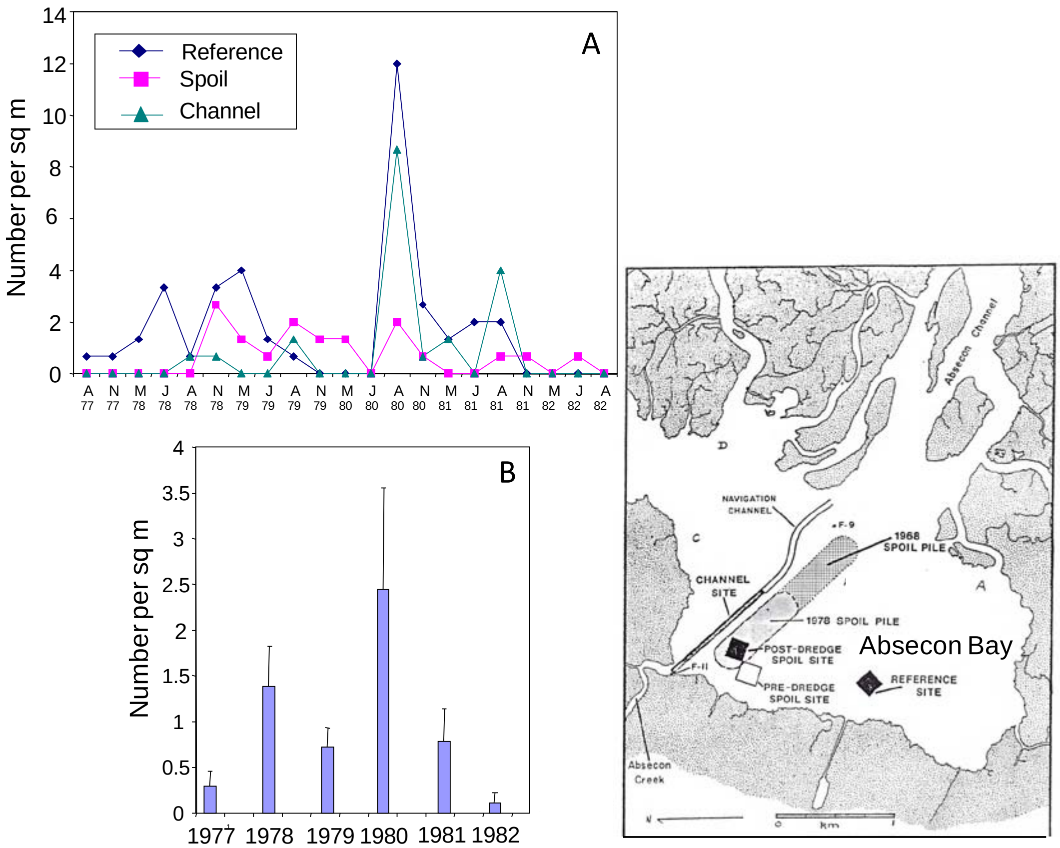


Figure 37. A). Relationship between the *Mercenaria mercenaria* spawning stock and recruiting year classes (2-yr-old clams) in numbers m^{-2} for the Islip Town portion of Great South Bay, NY (Bricelj, 2009, modified from Kraeuter et al. 2005). Red arrow marks the point where the fitted curve intercepts the X axis (~0.8 adults m^{-2}) (see text). The curves represent the best fit for log (blue) and 2nd order polynomial (green) function models, which provided the most realistic fit to the data (linear and power functions were excluded as they led to unrealistic predictions). The fitted equations and coefficients of determination (R^2) are shown.
B) Temporal changes in the number of recruits per adult between 1979 and 2003 in Islip Town, GSB. Horizontal red line indicates the 1979-2003 mean for recruits per adult (Bricelj 2009, modified from Kraeuter et al. 2008). Adults = clams ≥ 2 year old. Brown arrows mark years of intense brown tides (≥ 400,000 cells mL^{-1}).

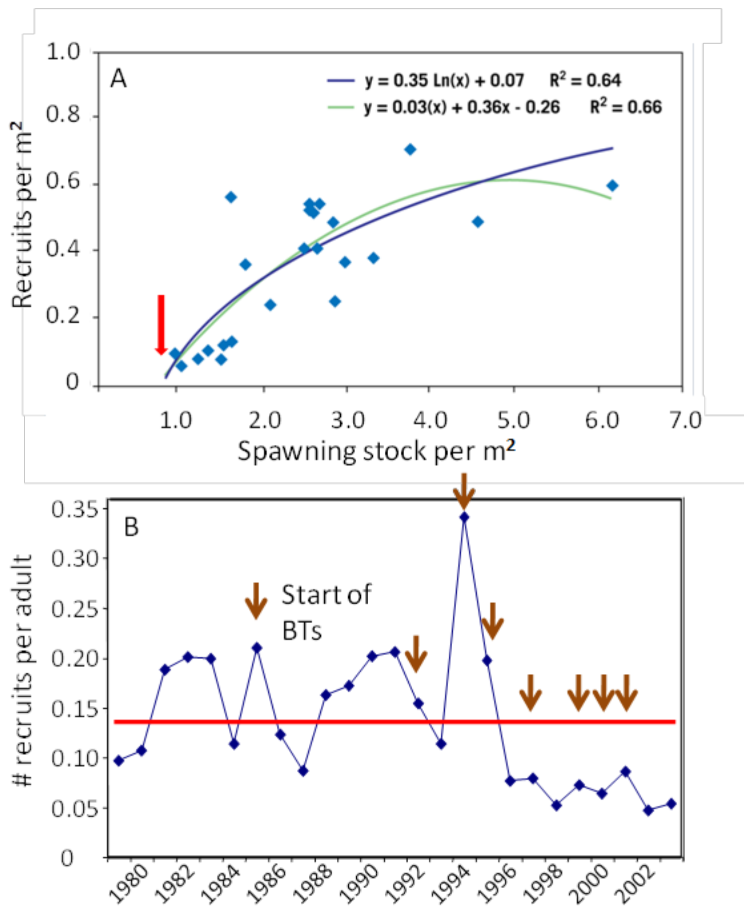


Figure 38. Upper graph: Weekly shell growth rate of hard clam juveniles, 4 size groups, 5 replicates per group, 2.5 to 12 mm SL held in 2" diameter upwellers (25 clams per upweller) at commercial shellfish hatchery in Tuckerton, NJ, during summer (May 20 to August 27, 2005 and May 31 to Sept. 13, 2006). Seed were replaced every 3 to 4 weeks with new individuals. Clams received ambient seawater (temperature records shown in lower graphs).

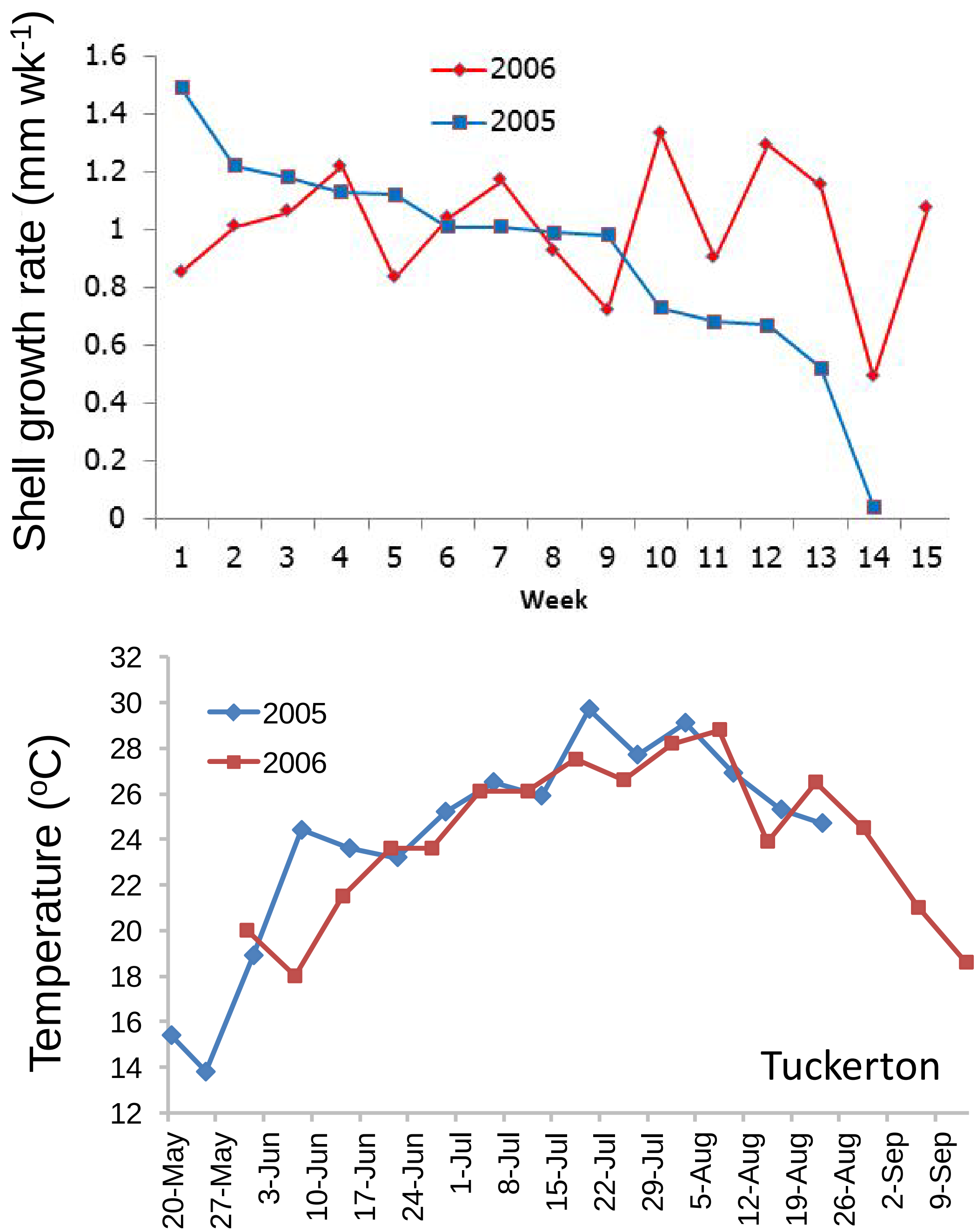


Figure 39. Size (length) at age growth curves for *Mercenaria mercenaria* obtained for populations in Barnegat Bay near the Oyster Creek Power Plant (Kennish and Loveland 1980), and Little Egg Harbor (Kraeuter et al. 2003), compared to those for hard clam populations in Great South Bay, NY (Buckner 1984 and Laetz 2002).

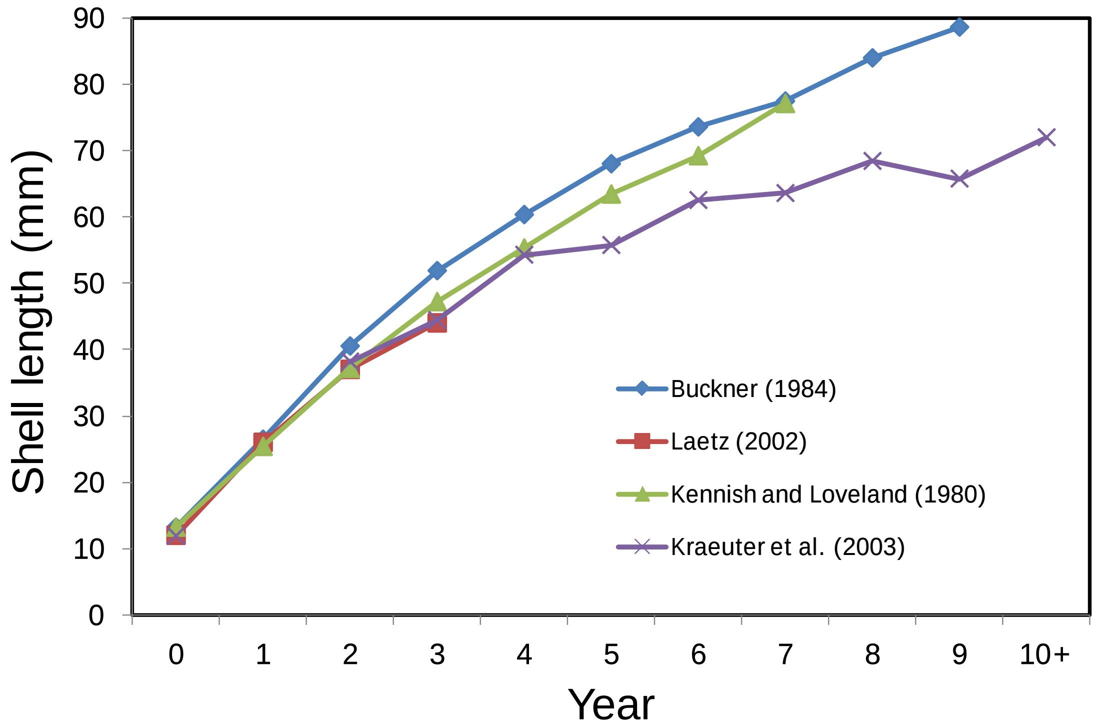


Figure 40. Shell length of a hard clam cohort that settled at two sites in the Absecon Bay, NJ (data plotted from Durand and Gabry 1984, and fitted to linear equations).

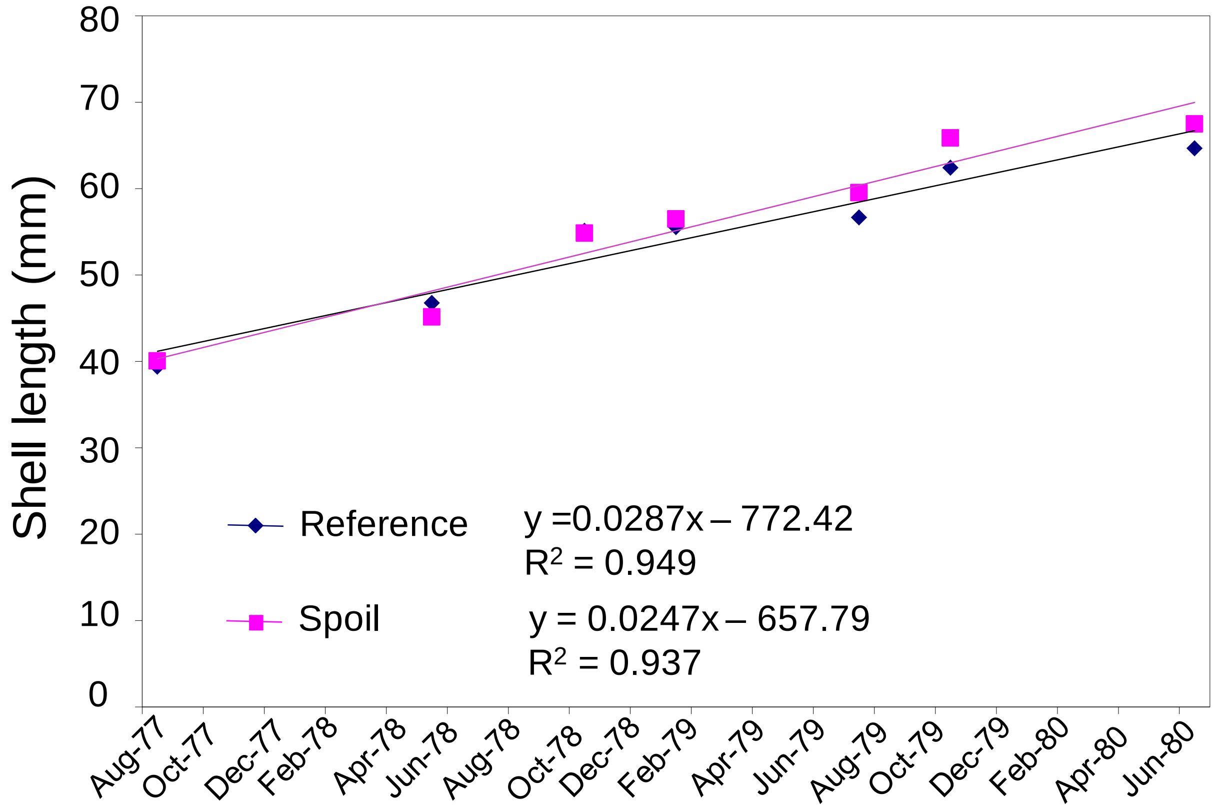


Figure 41. **A)** Annual summertime (June-August) catch of blue crabs, *Callinectes sapidus*, in Delaware, New Jersey (NJ) and Barnegat Bay (BB), and the percentage of the total NJ catch represented by BB (from Jivoff 2011) between 1996 and 2006; **B)** Comparison of total catch with catch per unit effort of blue crabs in NJ, 1996-2006 (Jivoff unpublished data).

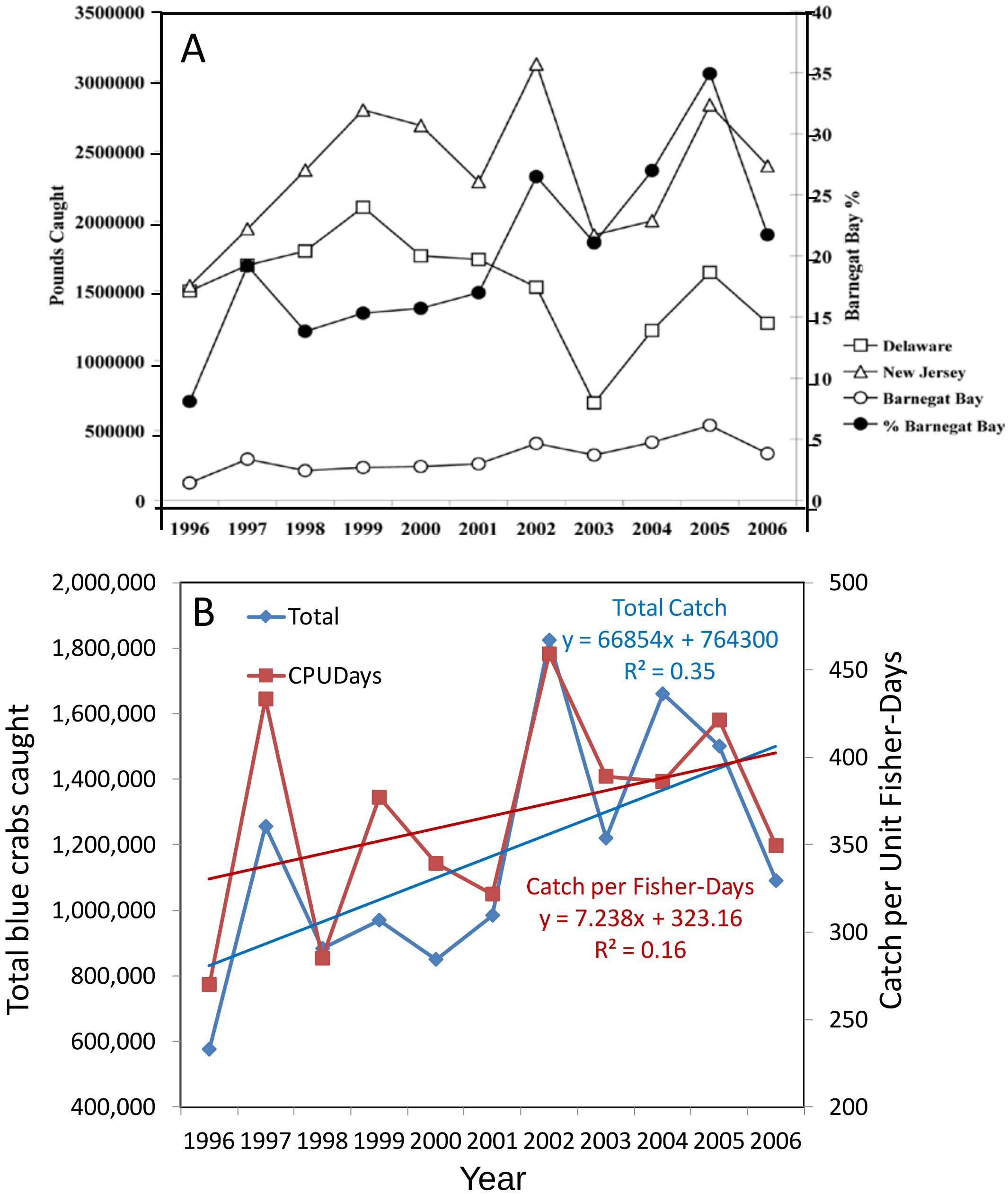


Figure 42. Effects of shell plantings on hard clam recruitment in Little Egg Harbor (from Kraeuter et al. 2003). Clams < 10 yrs old recruited during the 10 years of shell plantings; the remainder were present at the site prior to the start of the shelling experiment. Values represent means ± 95% confidence intervals.

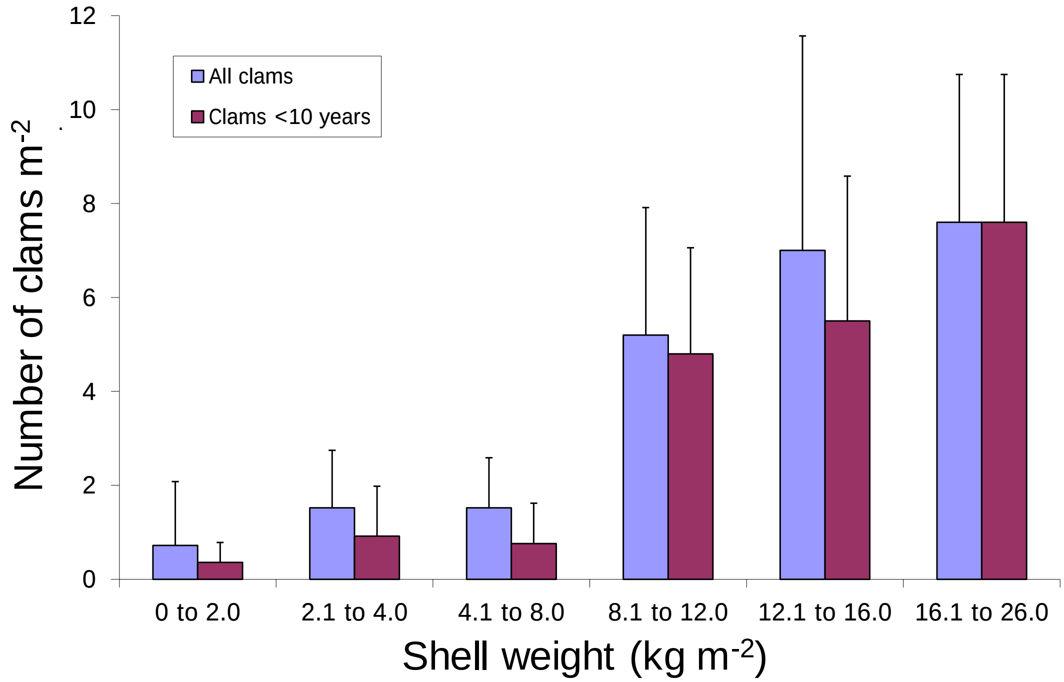


Figure 43. Recirculating upwellers operated by the ReClam The Bay Inc. volunteer program at one of seven locations in BB-LEH (Island Beach State Park). Insets on the left show a top-down view of the silos containing juvenile hard clams.

Figure 44. Map showing the locations of previous plantings of hard clam seed conducted by NJDEP Division of Fish and Wildlife in the Sedge Island Marine Conservation Zone (MCZ), Barnegat Bay (modified from a figure provided by Gustavo Calvo, NJDEP). Seed plantings in 2010- 2011 were conducted in Site A (around Dorsett Is.) and in 16 two acre (= 4,046 m^2) plots within Johnny Allens Cove – Buster Islands (area marked by the red polygon) (see text).

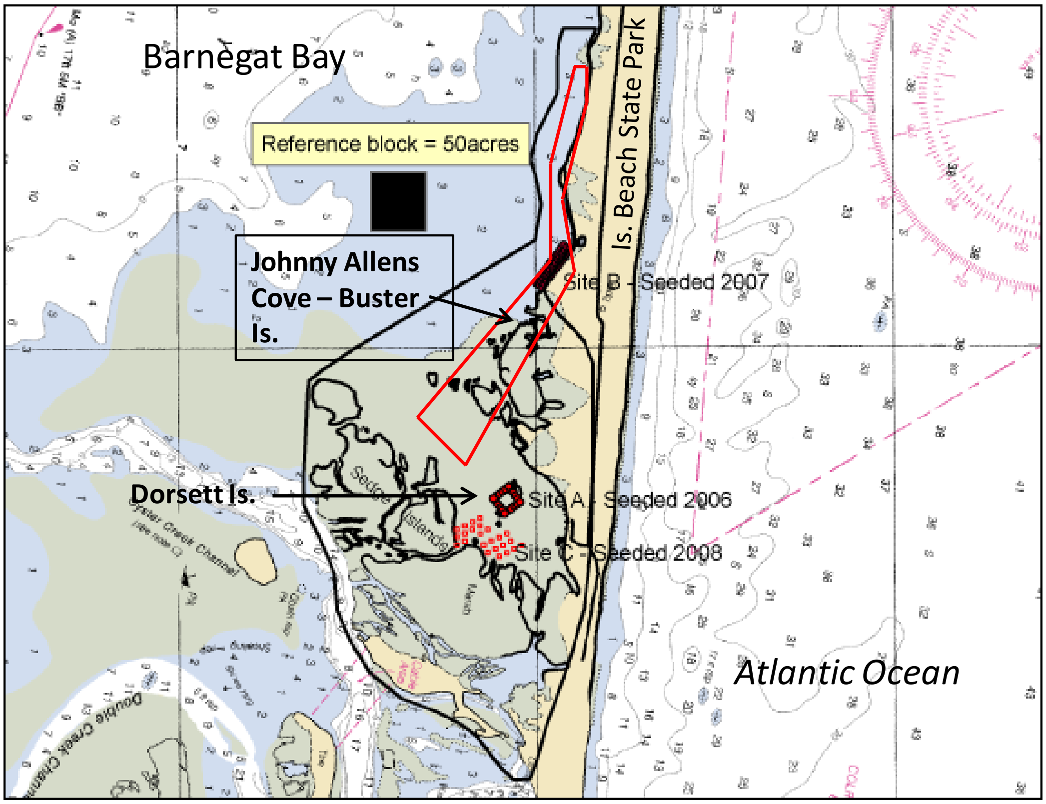


Figure 45. *Mercenaria mercenaria*: selected notata strain (heterozygote and homozygote genotypes) produced by commercial hatcheries (clams shown obtained from George Mathis, Mathis Clam Farm, NJ) and "wild" or unselected hard clams.

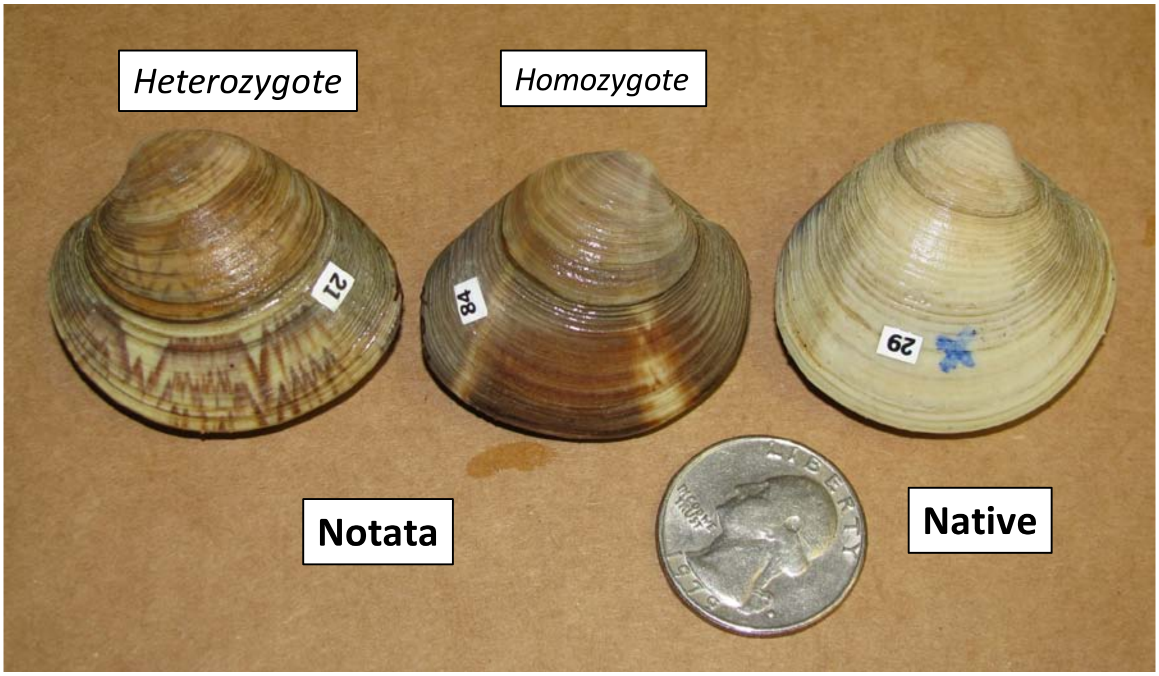
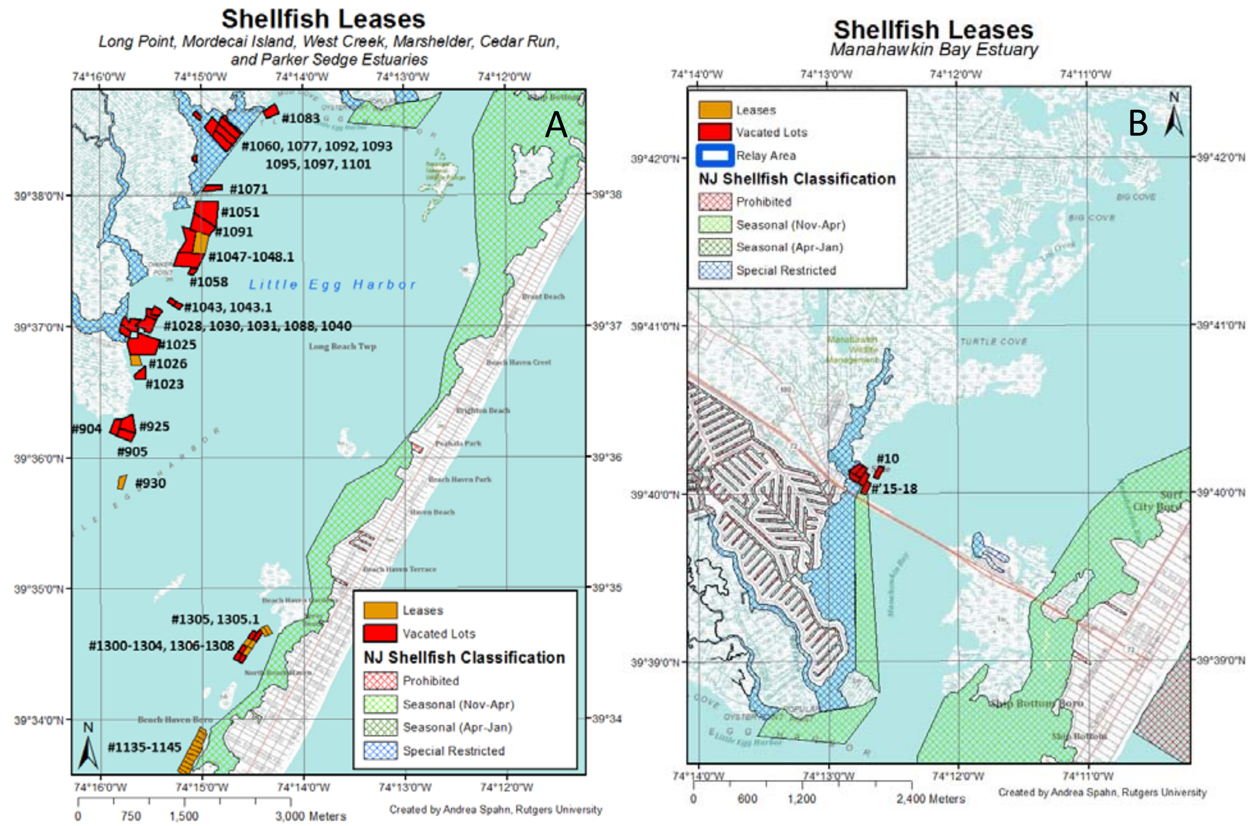
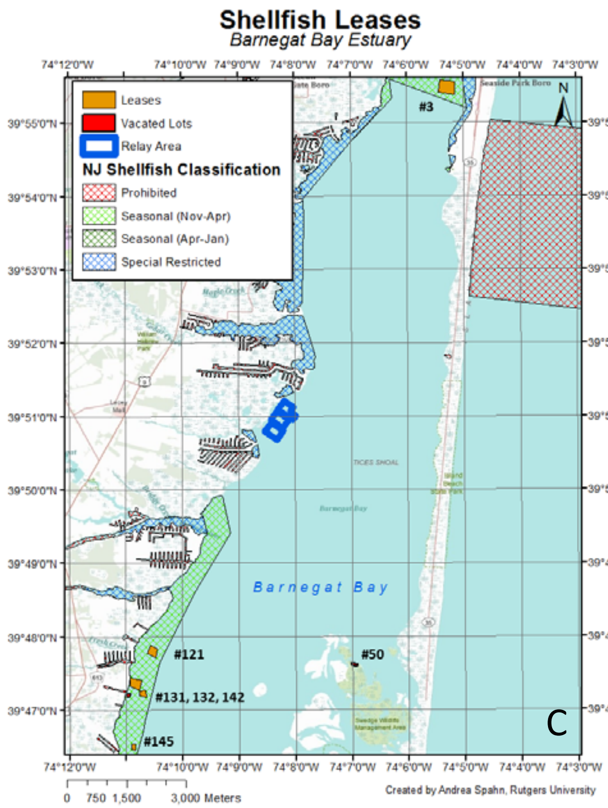
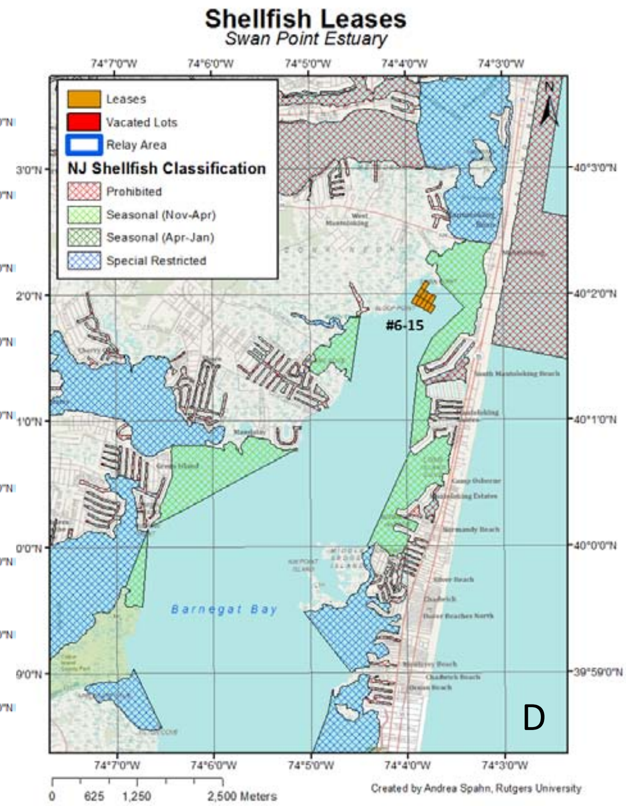


Figure 46. Maps of the BB-LEH estuary showing location of shellfish bottom leases (see sec. 10), vacated lots, areas used in the past for clam relaying and status of waters based on NJ shellfish classification (see sec 5): A. Upper Little Egg Harbor (LEH), B. Manahawkin Bay, C & D. Barnegat Bay, and E. Lower LEH.




Shellfish Leases
Barnegat Bay Estuary
Leases
Vacated Lots
Relay Area
NJ Shellfish Classification
Prohibited
Seasonal (Nov-Apr)
Seasonal (Apr-Jan)
Special Restricted
#3
#121
#131, 132, 142
#145
#50
Barnegat Bay
C
0 750 1,500 3,000 Meters
Created by Andrea Spahn, Rutgers University


Shellfish Leases
Swan Point Estuary
Leases
Vacated Lots
Relay Area
NJ Shellfish Classification
Prohibited
Seasonal (Nov-Apr)
Seasonal (Apr-Jan)
Special Restricted
#6-15
Barnegat Bay
D
0 625 1,250 2,500 Meters
Created by Andrea Spahn, Rutgers University

Shellfish Leases

Gaunt Point, Big Mud Creek, Rose Point, Parker Cove, Middle Island and Weir Creek Estuaries

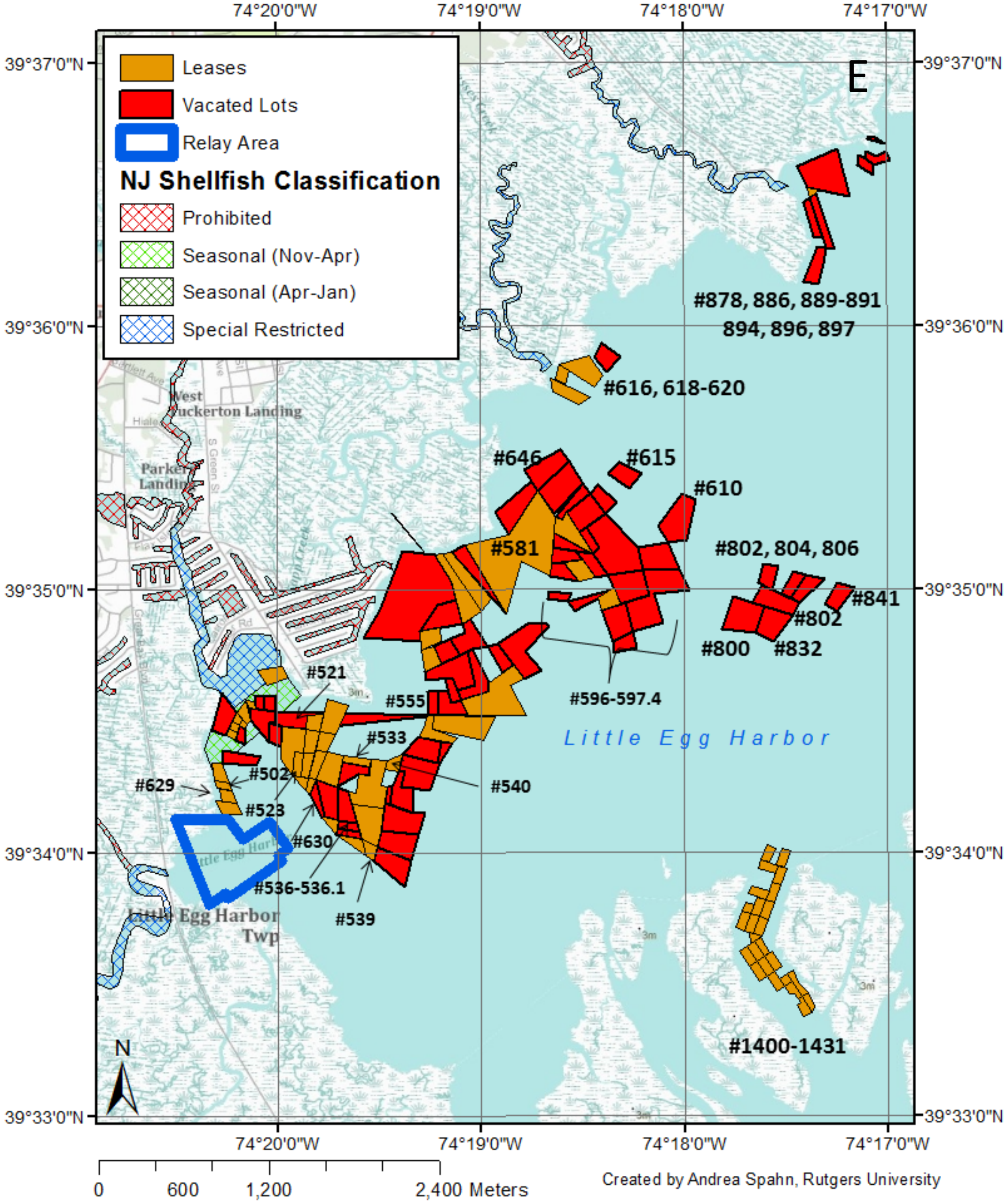


Figure 47. Map of Middle Island Channel, Little Egg Harbor (LEH), proposed shellfish leases (from Normant 2009) with densities of hard clams (see text for details). Low density (< 0.2 clams ft^{-2}), moderate density (0.2 to < 0.5 clams ft^{-2}) and high density ($\geq$ 0.5 clams ft^{-2}). Polygon marked in green indicates the presence of SAV. Inset shows the general location of the surveyed area within southern LEH.

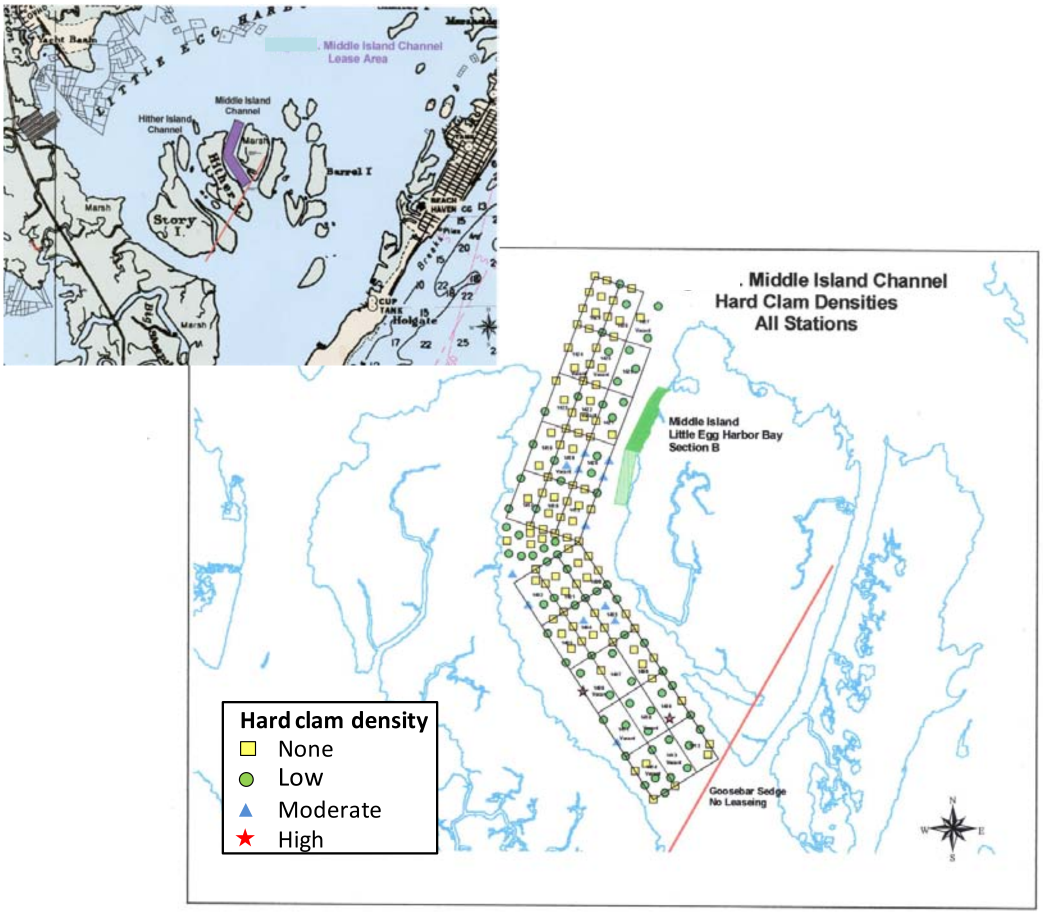


Figure 48. Percentage of the total area surveyed in 2009 in response to a shellfish lease application in Middle Island Channel, southern Little Egg Harbor that yielded varying densities of hard clams (densities as in Fig. 42). **A)** Overall, combining all data, **B)** in shallow sampling stations (n = 129) using a hand rake, **C)** in deep water stations (n = 44) using a hydraulic dredge. (Plotted from raw data in Normant 2009; see text).

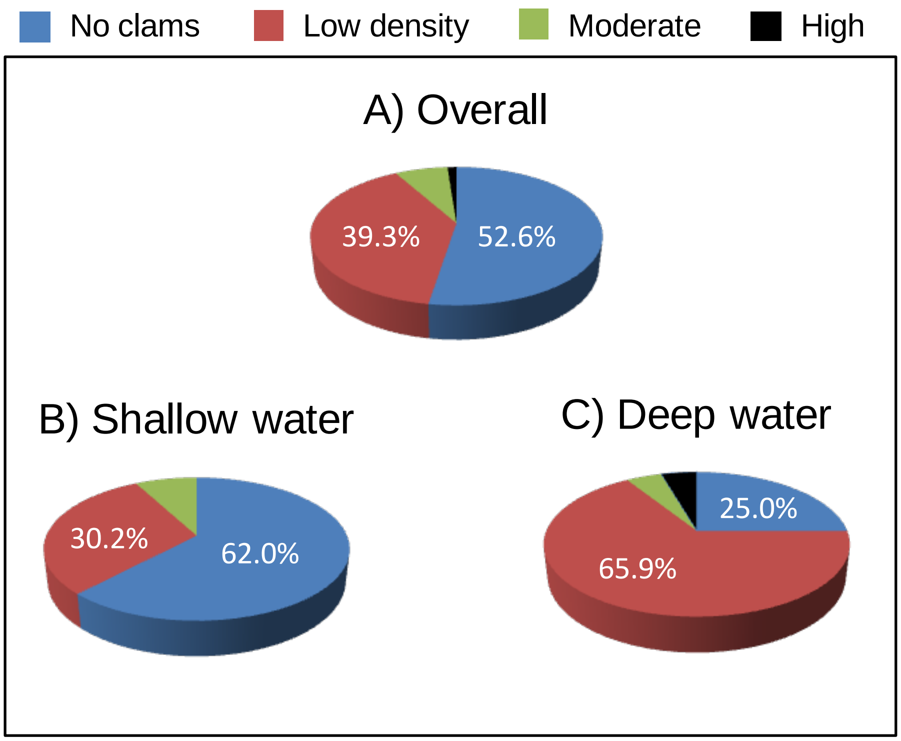
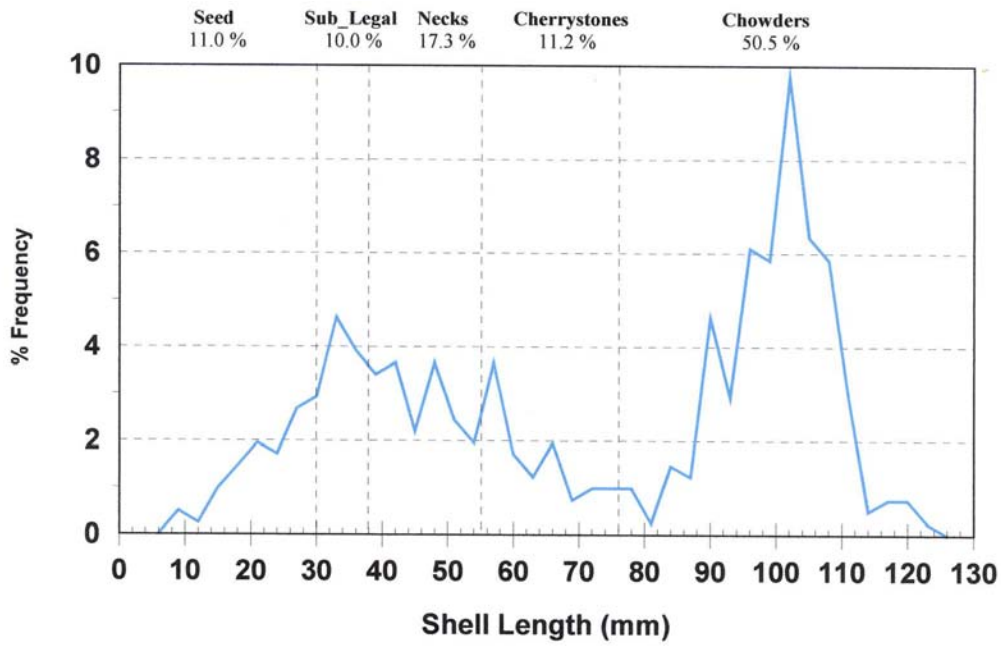


Figure 49. Size (length)-frequency distribution (3 mm groupings) and percentage of market size categories of hard clams collected in Middle Island Channel (all stations shown in Fig. 42 combined (from Normant 2009). N = 410 hard clams, mean shell length = 71.4 mm.



List of Tables

Table 1. General characteristics of the BB-LEH estuary in relation to other selected mid-Atlantic coastal lagoonal ecosystems, including the total nitrogen and phosphorus load from the watershed to the receiving estuary (see sec. 2b.vi**)**. From Kennish et al. (2007) unless specified. Depth is that at mean low water. MD coastal bays include Assawoman Bay, St. Martin River, Isle of Wight Bay, Sinepuxent Bay, Newport Bay and northern Chincoteague Bay.

Coastal Bay	Watershed area (km^2)	Population in watershed	Surface area (km^2)	Depth (m)	Tidal height (m)	Exchange time (days)	Mean salinity (mg kg^{-1})	TSS (millions kg y^{-1})	Total N (millions kg y^{-1})	Total P (millions kg y^{-1})
BB-LEH, NJ	1,730	575,000[1]	280	1.5	0.24	24-74[2]	20	74.0	1.19	0.17
MD Inland Bays	283	15,166	54	1.92	0.67	253	28	1.88	0.24	0.03
Chincoteague Bay, VA	487	5,706	335	1.94	0.50	183	29	6.07	0.08	0.01
Great South Bay, NY	1,733	2,084,075	383	1.10	0.57	7-44[3]	24-28[4]	153.0	4.69	0.90

[1]Kennish and Fertig (2012); [2]Guo et al. 2004; [3]Kinney and Valiela (2011); exchange rate based on data reviewed by Kinney & Valiela (2011), but = 7-10 d based on their own calculations; [4]Lively et al. 1983 (mean of 23.6 for central and eastern GSB, and mean of 28.3 for West Bay).

Table 2. Development of *Mercenaria mercenaria* fertilized eggs, and survival and growth of larvae 10 days post-fertilization as a function of temperature and salinity, as determined experimentally by Davis and Calabrese (1964). Ranges for optimum development are marked by horizontal bars.

Eggs Developing Normally (%)

	Temperature								
Salinity	32.5	30	27.5	25	22.5	20	17.5	15	12.5
27	39	81	93	95	92	95	94	24	0
22.5	1	36	65	79	73	73	52	1	1
20	0	0	0	5	0	0	0	0	0
17.5	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0

Larvae Surviving after 10 days (%)

	Temperature								
Salinity	32.5	30	27.5	25	22.5	20	17.5	15	12.5
27	77	83	81	75	87	75	71	61	56
22.5	48	84	87	83	88	76	70	56	46
20	16	72	84	76	77	78	62	50	40
17.5	1	76	74	83	85	69	45	50	49
15	0	25	22	75	53	43	58	36	47
12.5	0	1	0	12	0	9	12	19	39

Increase in Length after 10 days (%)

	Temperature								
Salinity	32.5	30	27.5	25	22.5	20	17.5	15	12.5
27	65	98	83	93	83	71	53	30	16
22.5	61	91	85	88	83	68	48	25	12
20	54	85	87	82	80	60	39	17	5
17.5	5	63	68	66	59	36	21	5	1
15	0	12	17	31	20	9	3	1	0
12.5	0	0	0	2	0	0	0	0	0

Table 3. Microalgal species by taxonomic group that can be potentially toxic and/or are known to be a poor food source for *Mercenaria mercenaria* (see text) and have been previously reported in BB-LEH by Olsen & Mahoney (2001). W = cell width; L = cell length.

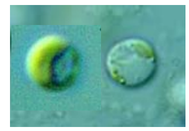
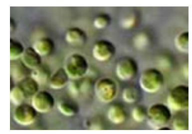
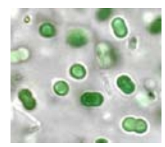
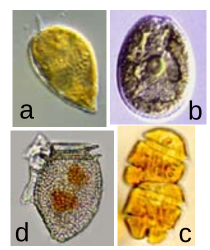
ALGAL TAXONOMIC GROUP	CELL SIZE (µm)	
Pelagophyceae		
Aureococcus anophagefferens	1-2	
Chlorophyceae (green algae)		
Nannochloris spp. (e.g. *N. atomus)*	1-3.5	
Chlorella spp.	~5	
Nannochloropsis (= *Stichococcus*) spp.	1-2	
Chlamydomonas sp.		
Cyanobacteria (blue-green algae)		
Synechococcus spp	1.5-2.5	
Dinophyceae (dinoflagellates)		
[a]*Prorocentrum minimum*	14-22 L; 10-15 W	
[b]*Prorocentrum lima*	32-50 L; 20-28 W	
[c]*Cochlodinium polychrykoides*	30-40 L; 20-30 W	
[d]*Dinophysis acuta*; *D. acuminata*	54-94 L; 43-60 W	

Table 4. Pumping rate (= clearance rate, CR, when particles are >3-4 µm and thus retained by the gill with 100% efficiency) of various commercial size classes of *Mercenaria mercenaria* based on [a]Hibbert's (1977) allometric equation relating CR to shell length (SL) using natural particulates at 25°C ($CR = 0.063L^{0.834}$, where CR = in L h^{-1}, and L = SL in mm, and based on [b]Doering et al.'s (1986) equation: CR (ml min^{-1}) = $L^{0.96}$ (cm) x $T^{0.95}$ x 0.339, with T = 25°C. Values are representative of ~maximum seasonal pumping rates under field conditions, as feeding rates increase with seasonal temperature up to ~ 25-28°C. Determination of bivalve CRs on natural particulates typically yield lower values than those obtained in the laboratory by feeding algal cultures (Powell et al. 1992), and are thus used here as more representative of natural conditions.

Size class	Mean SL	Pumping rate (L h^{-1})
Sublegal	33.5	1.18[a]; 1.38[b]
Littleneck	46.5	1.55[a]; 1.89[b]
Cherrystone	66.0	2.07[a]; 2.65[b]
Chowder	>76.0	>2.33[a]; 3.03[b]

Table 5. Comparison of clam population data from Little Egg Harbor, NJ, between 1986/87 and 2001 based on the number m^{-2}, the percentage of the various size classes and the percent reduction per size class. SL = seed (30-37 mm SL), LN = Littleneck (38-55 mm SL), CS = Cherrystone (56-75 mm SL), and CH = Chowder (> 76 mm SL).

	SL	LN	CS	CH	Total
			number m^{-2}		
1986/87	0.090	0.280	0.910	1.290	2.570
2001	0.013	0.081	0.253	0.529	0.876
			% of total		
1986/87	3.50	10.89	35.41	50.19	
2001	1.48	9.25	28.88	60.39	
			% Reduction		
	85.56	71.07	72.20	58.99	65.91

Table 6. Known predators of *Mercenaria mercenaria* (L = larvae; J = juveniles, typically ≤ 20 - 25 mm shell length, SL; A = adults) in the Barnegat Bay-Little Egg Harbor estuary. Evidence of hard clam predation, in the field and/or in the laboratory derived from Kraeuter (2001) unless specified. Clam sizes (SL) vulnerable to various predators from reviews by Bricelj (1992) and Kraeuter (2001).

Class/Species	Common name	Prey Stage/Size
CTENOPHORA		
Mnemiopsis leidyi	Comb jellyfish	L
NEMERTEA		
Cerebratulus lacteus	Ribbon worm	Presumed; J
MOLLUSCA		
Mercenaria mercenaria	Hard clam	L
GASTROPODA		
Neverita (=Polinices) duplicata	Shark eye, moon snail	J, A (up to ~ 55 mm)
Urosalpinx cinerea	Atlantic oyster drill	J
Eupleura caudata	Thick-lip drill	J
Busycon carica	Knobbed whelk	J, A ([a]up to 170 mm)
Busycotypus (= Busycon) canaliculatus	Channeled whelk	J, A
ARTHROPODA		
Limulus polyphemus	Horseshoe crab	small J
Palaemonetes vulgaris	Common grass shrimp	small J (< ~ 1 mm)
Palaemonetes pugio	Daggerblade grass shrimp	small J (< ~ 1 mm)
Crangon septemspinosa	Sand shrimp	small J (≤ ~1 mm)
Pagurus longicarpus	Long clawed hermit crab	J (≤ ~ 3 mm)
Cancer irroratus	Rock crab	J (up to 15 mm)
Carcinus maenas	Green crab	J, A (up to ~30 mm)
Ovalipes ocellatus	Lady crab	J (≤ ~ 28 mm)
Calllinectes sapidus	Blue crab	J, A (up to ~40 mm)
Dyspanopeus (=Neopanope) sayi	Mud crab	J (≤ ~12 mm)
Panopeus herbstii	Black-fingered mud crab	J, A (up to ~35 mm)
Eurypanopeus depressus	Flatback mud crab	J
ECHINODERMATA		
Asterias forbesi	Forbes sea star	J, A (up to ~72 mm)
CHORDATA		
Pisces		
Rhinoptera bonasus	Cow-nose ray	J, A[b]
Acipenser oxyrhunchus	Atlantic sturgeon	J
Pseudopleuronectes americanus	Winter flounder	J - siphon nipping

Paralichthys dentatus	Summer flounder	J – siphon nipping
Sphaeroides maculatus	Puffer fish	J; presumed
Tautoga spp.	Tautog	J (< 10 mm)
Aves		
Anas rubripes	Black duck	J
Marila marila	Scaup	J
Haematopus ostralegus	Oystercatcher	J, A (< 70 mm)
Larus argentatus	Herring gull	J, A (< 90 mm)

[a]Prey size given for Busycon sp. without differentiating between whelk species.

[b]Adult rays are able to consume hard clams up to 31-32 mm in shell thickness, regardless of the clams' shell length, due to limitations of their jaw gape (Fisher et al. 2011). Rays preferred *M. mercenaria* over oysters, *Crassostrea virginica*, as prey.

Table 7. Summary of bottom plantings of hard clam seed (20-25 mm SL) conducted in the Sedge Island Marine Conservation Zone (MCZ), Barnegat Bay (see Fig. 18) in 2010 and 2011 by season and location (based on Calvo 2011).

Area Planted km^2	Season/Yr	# clams planted	Clam planting density lot^{-1}, # m^{-2} (Range)
Johnny Allens Cove 0.032	Fall 2010 (Oct. 26 to Nov. 4[a])	545,000	12.4 – 24.7
Johnny Allens Cove 0.081	Spring 2011 (May 5 to June 2)	960,000	8.6 – 13.0
Johnny Allens Cove 0.016	Fall 2011 (Oct. 25)	1,882,000 87% notata	21.9 – 24.7
off Dorset Island 0.020	Fall 2011 (Sept. 11)	276,380	13.6

[a]One of 4 plots received 60,000 clams in Nov. 4/2011 and was reseeded with 40,000 clams in May 25/2011

Table 8. Life tables from Connell, 1983 and average data from stations 2, 5, 6, and 9 (Kennish 1978). Connell data base adjusted from 10,000 to 1,000. Kennish average data adjusted from 1000 to 5.8 to match the Connell data at age 1. Bold-faced ages are for years 1 to 8. L_x = number of live individual at the beginning of interval x. d_x = number of individuals dying during interval x. $1000q_x$ = mortality rate per 1000 alive at the beginning of interval x. e_x = mean life-time remaining for individuals attaining interval x.

		Connell, 1983				Kennish, 1978		
Age (mo.)	lx	dx	1000qx	ex	lx	dx	1000qx	ex
1-2	1000	762.200	76.2	0.11				
2-3	238.7	135.200	56.9	0.19				
3-4	102.7	46.100	44.9	0.28				
4-5	56.6	20.900	36.9	0.37				
5-6	35.6	11.200	31.5	0.45				
6-7	24.4	6.700	27.5	0.54				
7-8	17.7	4.300	24.3	0.62				
8-9	13.5	2.900	21.5	0.70				
9-10	10.5	2.100	20	0.78				
10-11	8.5	1.500	17.6	0.85				
11-12	7	1.100	15.7	0.93				
12-13	5.8	0.900	15.3	1.01	5.8	0.07	12.07	4.84
13-14	4.9	0.700	14.3	1.08				
14-15	4.2	0.600	13.3	1.16				
15-16	3.7	0.500	12.5	1.22				
16-17	3.2	0.400	11.8	1.29				
17-18	2.8	0.300	11.2	1.35				
18-19	2.5	0.300	10.6	1.42				
19-20	2.2	0.200	10.1	1.48				
20-21	2	0.200	9.6	1.54				
21-22	1.8	0.200	9.2	1.60				
22-23	1.7	0.100	8.8	1.65				
23-24	1.5	0.100	8.4	1.71				
24-25	1.4	0.100	8.1	1.76	5.73	0.19	33.16	3.89
36-37	0.6	0.030	5.5	2.25	5.54	0.24	43.32	3.01
48-49	0.3	0.010	4.2	2.46	5.3	0.65	122.64	2.12
60-61	0.2	0.010	3.4	2.40	4.65	1.85	397.85	1.35
72-73	0.1	0.004	2.8	2.05	2.8	1.79	639.29	0.91
84-85	0.1	0.002	2.4	1.41	1.01	0.86	851.49	0.65
96-97	0.078	0.002	2.1	0.49	0.15	0.15	1000	0.50

Appendix I. Lease area survey data from NJDEP, Division of Shellfisheries for Barnegat Bay and Little Egg Harbor. SL = Sublegal, LN = Littleneck, CS = Cherrystone and CH = chowder (see Fig. 46 A through E for lease locations and sec. 6 a. iii. for sampling details). Size ranges for each commercial size class given in the text. Data shown represent all lease survey data available.

Lease #	Lease Sector	Date	Live % <SL	% SL	% LN	% CS	% CH	Live # ft^{-2}	SD	Live # m^{-2}	Dead % <SL	% SL	% LN	% CS	% CH	Dead # ft^{-2}	SD	Dead # m^{-2}
2	C	Mar-04	0	6.7	13.3	80	0	0.18	0.385	1.90						0.08	0.288	0.91
6,7	D	Sep-12	0	0.6	62.5	28.1	7.8	0.04	0.065	0.45	0	0.8	88.4	5.4	5.4	0.07	0.258	0.71
8,10	D	Apr-06	0	0	25	75	0	0.02	0.091	0.20	0	0	0	60	40	0.13	0.446	1.44
9	C	Mar-04	0	0	0	100	0	0.63	1.375	6.83	0	0	0	100	0	0.00	0.003	0.01
9	D	Apr-06	0	0	50	33.3	16.7	0.01	0.017	0.10	0	0	0	0	100	0.00	0.006	0.02
10	C	Aug-97	0	0	34.8	60.9	4.3	0.02	0.018	0.16	0	0	20	60	20	0.01	0.010	0.06
10.1	C	Nov-00	0	0	0	100	0	0.01	0.011	0.08	0	0	0	0	100	0.00	0.005	0.02
11	D	May-09	0	0	37.5	37.5	25	0.01	0.016	0.09	0	0	14.3	28.6	57.1	0.01	0.018	0.12
13.01	B	Dec-99	0	0	0	50	50	0.54	1.198	5.81		0	25	50	25	0.00	0.006	0.02
15	C	Sep-96	0	0	0	92.9	7.1	0.01	0.016	0.12	0	0	0	0	0	0.00	0.000	0.00
17	C	Apr-91		0	17	70	13	1.02	0.021	10.92		0	0	83.3	16.7	0.00	0.001	0.00
20,22,24	C	Nov-95	0	0	0	100	0	0.00	0.003	0.01	0	0	0	0	0	0.00	0.000	0.00
21	C	Aug-95	0	0	30	70	0	0.12	0.271	1.28		0	11.1	63	25.9	0.12	0.027	1.25
132	C	Jun-08	0	0	22.2	77.8	0	0.02	0.030	0.19	0	0	20	80	0	0.00	0.016	0.05
261	C	Mar-88						0.43		4.63								0.00
263	C	Sep-90	0	0	0	0	0	0.00	0	0.00		0	0	100	0	0.00	0	0.03
408.1		May-88						0.97		10.44								0.00
485	B	Aug-01	0	0	25	50	25	0.00	0.008	0.04	0	0	0	0	100	0.00	0.008	0.02
502	B	Feb-90						0.15	0.274	1.59						0.00	0.003	0.01
503	B	Jul-88						0.07		0.75								0.00
521	B	May-02	0	25	0	50	25	0.19	0.543	2.04	0	0	25	0	75	0.02	0.030	0.19
523	B	Jun-06	0	0	0	0	0	0.50	0.837	5.38	0	0	0	0	0	0.00	0.000	0.00
533	B	Mar-01	0	0	0	0	100	0.00	0.000	0.00		0	14.2	42.9	42.9	0.00	0.000	0.00
536	B	Sep-89	0	0	4.3	42.1	53.6	0.08	0.105	0.90	0	0	12.5	87.5	0	0.02	0.016	0.22
536.1	B	Sep-89						0.60	0.577	6.49						0.07	0.126	0.79
536,536.10		Oct-99	0.7	0	0	15.5	83.8	1.67	2.887	17.93	2.4	2.4	14.3	61	19	0.00	0.000	0.00
539	B	Apr-92	0	0	0	0	0	0.08	0.277	0.83	0	100	0	0	0	0.00	0.002	0.01
539,646	B	Oct-99	50	0	0	0	50	0.25	0.500	2.69	0	0	0	10	90	0.00	0.000	0.00
540		Mar-01	0	0	0	0	100	0.00	0.000	0.00		0	14.2	42.9	42.9	0.00	0.000	0.00
555	B	Apr-91	0	0	0	56.25	43.75	1.43	3.489	15.41	0	0	0	56.25	43.75	0.02	0.015	0.23
596,596.10	B	Aug-90	0	0	0	40	60	0.10	0.307	1.12	0	0	0	67	33	0.01	0.015	0.09
597,597.1,.2,.3,.4	B	Apr-90	0	0	0	16.7	83.3	0.03	0.032	0.30	0	0	0	66.7	33.3	0.00	0.019	0.02
616	B	Jun-08	0	0	0	0	0	0.00	0.000	0.00	0	0	0	0	100	0.08	0.277	0.83
629	B	May-05	0	12.5	25	62.5	0	0.13	0.483	1.36	0	0	0	0	0	0.00	0.000	0.00
630	B	May-02		5.8		17.6	76.5	0.25	0.826	2.70	0	0	0	33.3	66.7	0.02	0.031	0.20
630	B	Jun-06	0	0	0	0	0	0.00	0.000	0.00	0	0	0	0	0	0.00	0.000	0.00
646		Sep-89	0	0	0	0	100	0.32	0.478	3.42	0	0	33.3	33.3	33.4	0.33	0.500	3.58
646,536.1,536	B	Sep-89	0.7	0	0	15.5	83.8	2.63	3.983	28.33	2.4	2.4	14.3	61	19	0.11	0.033	1.13
836	B	Jul-88						0.65		6.99								0.00
878	B	Jun-90	0	0	0	23.5	76.5	0.17	0.098	1.79	0	0	0	46	54	0.03	0.030	0.38
897	B	Feb-91	0	0	38.3	55.3	6.4	0.52	1.084	5.56	0	0	0	37.5	62.5	0.00	0.004	0.02
1019, 1023	B	Nov-90	0	0	0	100	0	0.00	0.000	0.01	0	0	0	89	11	0.00	0.002	0.00
1058.1	B	Apr-92		0	8.3	8.3	83.4	0.09	0.274	0.95						0.08	0.277	0.84
1097.1	B	May-85						0.04		0.46								0.00
1105	B	May-90	0	0	0	44.4	55.6	0.10	0.103	1.06	0	0	0	57	43	0.03	0.031	0.36
1304	B	Dec-99	100	0	0	0	0	0.25	0.707	2.69	0	0	0	66.7	33.3	0.00	0.007	0.05
1304	B	Sep-04	50	25	0	25	0	2.00	2.160	21.52	0	0	0	0	0	0.00	0.000	0.00
1305	B	Apr-91	0	0	100	0	0	0.08	0.277	0.83	0	0	0	100	0	0.00	0.002	0.01
1305.1	B	Oct-95	0	0	0	100	0	0.00	0.011	0.04	0	0	0	100	0	0.00	0.003	0.01
1305.3	B	Jun-97	0	0	0	100	0	0.01	0.033	0.14	0	0	0	0	0	0.00	0.000	0.00
1306, 1307, 1308	B	Dec-99	0	0	66.7	0	33.3	0.12	0.439	1.30		0	60	40	0	0.16	0.472	1.75
1458	C	Nov-91	0	0	0	100	0	0.01	0.017	0.14	0	0	6.25	50	43.75	0.03	0.046	0.31

Appendix II. Shorefront area survey data from NJDEP, Division of Shellfisheries for Barnegat and Little Egg Harbor Bays. SL = Sublegal, LN = Littleneck, CS = Cherrystone and CH = Chowder. Size ranges for each given in the text. Based on all available survey data.

		Live					Dead								
		%	%	%	%	%	%	%	%	%	%	Live	Live	Dead	Dead
Address	**Date**	**<SL**	**SL**	**LN**	**CS**	**CH**	**<SL**	**SL**	**LN**	**CS**	**CH**	**# ft^{-2}**	**# m^{-2}**	**# ft^{-2}**	**# m^{-2}**
Wescott Road	13-Jan-94	0	0	100	0	0	0	0	0	0	0	0	0.00	0	0.00
North 3rd street Surf City	07-Jul-94											0	0.00	0	0.00
1313 E. Mallard Drive	13-Oct-94											0	0.00	0	0.00
1710 Bay Terrace	29-Jan-96											0	0.00	0	0.00
11404 Sunset Terrace			2	57	55	5	0	0	0	37.5	62.5	0.82	8.79	0.05	0.57
1210 West Avenue	22-Feb-94											0.05	0.50	0.34	3.66
1467 Mill Creek Road	23-May-94	0	0	14.3	71.4	14.3	0	0	0	100	0	0	0.00	0	0.00
Lavenia Street	17-Jun-94	0	0	0	100	0	0	0	0	0	0	1.00	10.76	0	0.00
114 W. McKinley Avenue	07-Jul-94											0	0.00	0	0.00
Mill Creek Thorofare	16-Aug-94	0	0	23	71	6	0	0	0	100	0	0.62	6.67	0.06	0.60
1723 Mill Creek Road	13-Oct-94	0	0	50	0	50	0	0	0	100	0	0.06	0.63	0.03	0.31
Coghlin Avenue	28-Mar-95											0	0.00	0	0.00
Mill Creek	13-Jul-05	0	0	14.3	71.4	14.3	0	0	0	0	0	0.02	0.24	0	0.00