

The Hard Clam Research Initiative:



Factors Controlling *Mercenaria mercenaria* Populations in South Shore Bays of Long Island, NY

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NYSGI-T-09-001
February 2009

Acknowledgements

This hard clam synthesis report was funded under award NOAA NA16FL2699 from the National Marine Fisheries Service to the Research Foundation of State University of New York on behalf of New York Sea Grant. The statements, findings, conclusions, views, and recommendations are those of the author and do not necessarily reflect the views of any of those organizations. The five Hard Clam Research Initiative (HCRI) projects were funded under award numbers NOAA NA96FL0279 and NA16FL2699.

The author acknowledges the assistance of Cornelia Schlenk and Barbara Branca from New York Sea Grant in the preparation of this report, and Lorian Cody for her help with design, layout and graphics. The author also thanks HCRI investigators for their input and response to specific questions during the course of writing, for helpful discussions, and in some cases for preparing graphs of their data. This report also benefited from reviews and comments from HCRI researchers and members of the HCRI Advisory Board of an earlier version, and from review of the final draft by James Ammerman, Director of New York Sea Grant. New York Sea Grant thanks two additional, external peer reviewers for their assessment of and valuable comments on the final draft: Dr. Roger L. Mann (Virginia Institute of Marine Sciences, VA) and Dr. Victor S. Kennedy (Horn Point Laboratory, MD).

Preface

This synthesis report was commissioned by the New York Sea Grant Institute and is intended to summarize key results of five research projects funded through New York Sea Grant's Hard Clam Research Initiative (HCRI) between 1999 and 2008. These projects and their principal investigators are listed below as are the co-sponsoring partners.

The main goal in the preparation of this report is to achieve improved, science-based understanding of the factors controlling hard clam, *Mercenaria mercenaria*, populations in Long Island, New York's south shore estuaries, and thereby contribute towards better management and potential enhancement of a once highly productive regional resource. Particular emphasis is given in this synthesis to findings that have direct implications for management of these populations.

The report is thus not intended to provide a comprehensive summary of knowledge about hard clam populations in Great South Bay or other south shore areas, nor can it reflect the views of all participants in the HCRI. Material outside the scope of the five projects, and results of projects funded by other sources have, however, been included where they contribute information directly relevant to the findings of the projects supported by the HCRI. Other funding sources are duly acknowledged throughout this report.

The main sources of information for this report include: a) publications, b) manuscripts in preparation or in press kindly provided by the investigators of these projects, c) project progress reports submitted to New York Sea Grant, and d) material presented at a 2-day workshop sponsored by the New York Sea Grant Institute August 11 and 12, 2008, at the School of Marine and Atmospheric Sciences, Stony Brook University, to summarize findings of the HCRI among the participating investigators, and present these to the HCRI Advisory Committee and stakeholders. Some of the results of the HCRI await final analysis, write-up and publication in peer-reviewed journals and are thus included in their preliminary form as available.

Titles and Principal Investigators of Projects funded through the Hard Clam Research Initiative

Relationships between the timing of reproduction, fecundity, and egg composition to declines in hard clam recruitment
(PIs: R.I.E. Newell, S. Tettelbach, C. Gobler)

The trophic interaction between hard clams and natural assemblages of phytoplankton
(PIs: R. Cerrato, D. Lonsdale, G. Lopez, R. Flood, R. Armstrong, J. Levinton)

Modeling hard clam growth, survival and environmental interactions: what are the controlling factors?
(PIs: E. Hofmann, V. M. Bricelj, R. Grizzle, J. Klinck, J. Kraeuter, E. Powell, S. Buckner)

The effects of brown tide and plankton quality on hard clam larval growth and survivorship
(PIs: D. Padilla, C. Gobler)

*A modeling study of the growth, survival and recruitment of hard clam (*Mercenaria mercenaria*) larval and post-settlement populations*
(PIs: E. Hofmann, V.M. Bricelj, S. Buckner, J. Klinck, J. Kraeuter, E. Powell)

Funding Co-Sponsor Partners

- NOAA National Marine Fisheries Service
- Port Authority of New York and New Jersey
- South Shore Estuary Reserve
- New York Sea Grant

Additional Projects Cited

Supported by New York Sea Grant core federal funds:

- *Impact of predation by the ctenophore *Mnemiopsis leidyi* on larval mortality of *Mercenaria mercenaria** (PIs: D. Lonsdale, R. Cerrato)
- *Influence of ocean exchange on nutrients, plankton assemblages, submerged aquatic vegetation and shellfish within Long Island's South Shore Estuaries* (PIs: C. Gobler, B. Peterson)

Supported by NOAA-Ecology and Oceanography of Harmful Algae (ECOHAB) funds, grant #NA04NOS4780275:

- *The importance of blooms of brown tide, *Aureococcus anophagefferens*, in coastal lagoonal systems: coupling numerical simulation modeling and experiments to determine population effects on hard clam, *Mercenaria mercenaria*, individuals, cohorts and populations* (PIs: J. Kraeuter, V.M. Bricelj, E. E. Hofmann, J. Klinck, E. Powell, E. Ward)

Supported by the National Science Foundation (funding allocation to D. Padilla via the Intergovernmental Personnel Act)

- Research that led to the publication Przeslawski et al. 2008.

Executive Summary

This report, *The Hard Clam Research Initiative: Factors Controlling Mercenaria mercenaria Populations in South Shore Bays of Long Island, NY*, provides a synthesis of results from studies funded via the Hard Clam Research Initiative (HCRI) and related studies funded from other sources. The studies addressed the downward trend in hard clam populations in Long Island's south shore bays, an issue of both environmental and economic interest to the region.

The precipitous decline in abundance of hard clams, *Mercenaria mercenaria*, in Great South Bay (GSB) from the 1970s to the mid-1980s can now be clearly attributed to overfishing. A population dynamics model developed for hard clams in GSB determined that a sustained harvest rate greater than approximately 25 percent of the historical standing stock (a harvest level exceeded in the 1980s), either as proportional fishing or selective fishing for littleneck clams, would rapidly drive these populations to extinction. This model also predicted that the recovery time of the current clam population to maximum historical densities, following release of all fishing pressure, would take on the order of a decade or more.

The causes for the continued population decline during the 1990s, despite the greatly reduced fishing effort, have not been fully resolved, but potential contributing factors were identified by the HCRI. Some of these factors include: the occurrence of brown tide (BT) blooms, reduced reproductive success associated with low clam densities and/or reduced food quality, and predation.

- **Occurrence of brown tide.** Clam recruitment dropped and remained below the 1979-2003 mean starting in the mid-1990s, coinciding with a period of relatively frequent BT blooms of the toxic picoplankter, *Aureococcus anophagefferens*. Waning of blooms between 2002 and 2006, however, did not lead to population recovery; thus BT cannot be the only factor causing this later decline.
- **Reduced reproductive success.** A spawner-recruit relationship for hard clams was established, indicating that a minimum threshold density of spawning stock (exceeding approximately 0.8 clams per square meter) is necessary to sustain recruitment. Although refinement of this relationship is needed, mean densities of adult clams decreased to this level from the mid-1990s onwards. In addition, from 1996 onward the number of recruits per adult was about half that of earlier years. Recruitment failure may thus be due

to limited gamete fertilization success at these low densities which would reduce larval numbers, and/or reduced larval quality and metamorphic/post-metamorphic success. Low fecundities of clams in GSB relative to other mid-Atlantic south shore estuaries were documented by the HCRI in 2001.

- **Predation.** Analysis of long-term predator surveys showed that the decline in hard clam abundance could not be attributed to changes in the abundance of mud crabs, the dominant predator in GSB. The role of other predators that are poorly surveyed, e.g., blue crabs, cannot be excluded as a factor contributing to the more recent population decline.

HCRI research also examined the relationship between hard clam reproduction and food supply in south shore bays. The timing of peak reproductive condition and spawning in GSB did not differ between 2001 (a year of low or no BT depending on location) and 1979 (a pre-brown tide year), and were comparable among south shore estuaries (SSE) in NY, and Sandy Hook Bay, NJ. The estimated clam reproductive output varied greatly in 2001: it was highest in western bays (Sandy Hook and Middle Bay), intermediate in Shinnecock Bay (SB) and lowest within GSB. These differences could not be explained by differences in the total algal biomass as measured by Chlorophyll *a* (Chl *a*). **Reproductive effort was generally inversely related to the percent contribution of small phytoplankton species (less than 5 μm) to total Chl *a* and positively related to the condition index of clams the previous fall.** The occurrence of BT and the fall food supply before the temperature drops in one year may thus influence reproductive success the following year.

Strong spatial gradients in growth rates of juvenile hard clams in SSE were also documented. In both GSB and SB growth was maximal at mid-bay locations, where Chl *a* attained only intermediate levels. Growth was least near inlets where food quantity was presumably limiting, and at inner bay sites where algae smaller than 5 μm made the greatest contribution to algal biomass. Present conditions for clam growth and reproduction were superior in SB compared to GSB. **Overall, experimental data and model simulations generated by the HCRI indicated that food quantity, as measured by total Chl *a*, is a poor predictor of clam production for all life history stages, whereas differences in food availability (size-fractionated Chl *a*) and food quality (gross biochemical composition and/or algal species composition) have major effects on larval and juvenile growth, and adult condition.**

Small algae (smaller than 5 μm) clearly dominate phytoplankton biomass in GSB during intense BT outbreaks. Yet even in non-BT years (e.g. 2005) or at locations where intense BT did not occur (e.g. western GSB in 2001) small algae dominated the total summer phytoplankton standing stock in GSB. Juvenile and adult clams poorly retain this size fraction and many of its constituent species, such as green algae and cyanobacteria, are known to be a poor food source for hard clam larvae and juveniles. Pennate diatoms and dinoflagellates were also associated with a poor food supply for hard clams. **Improved characterization of the food supply for hard clams was identified as a critical research need by the HCRI.**

Model simulations, supported by experimental data, showed that the effect of BT on growth is inversely related to clam size, indicating that juveniles are more vulnerable to negative effects of BT than adults. Additionally, the main period of hard clam larval production in GSB as determined in a pre-BT year (1979) and in 2001, a non-BT year, occurred in June-July. This coincides with the typical mid-summer occurrence of BT, which poses a threat to larvae that are actively feeding on the plankton at this time. **Laboratory studies demonstrated that toxic BT cells in late exponential or stationary growth phase caused concentration-dependent reduction in growth of hard clam larvae.** At high BT concentrations, this will likely lead to a longer development period for the free-swimming larvae in the plankton, and thus result in greater risk of predatory mortality under field conditions. Larvae fed BT in the laboratory also accumulated very low levels of lipid reserves and showed individual variability in their response to BT. Effects of BT on larval recruitment success and the consequences of reduced larval recruitment on the adult population remain to be determined in the field.

Ecosystem-level changes have also been documented in SSE. The decline of hard clams in Long Island shallow bays and the absence of other benthic suspension-feeding macrofauna, documented in GSB, indicate that grazing pressure on the phytoplankton has shifted from the benthos to the zooplankton. Marked spatial variation in the abundance and composition of zooplankton throughout GSB was also documented. Preliminary evidence suggests that ctenophores (commonly known as comb jellies), a gelatinous zooplankton and a major predator of bivalve larvae, have increased in abundance in GSB. Preliminary experiments also suggest that the presence of actively feeding adult clams may, under some conditions, alter the phytoplankton community and thereby enhance juvenile clam growth, but interpretation of these data remains questionable.

Conclusions from the HCRI are somewhat constrained by the relatively short (1- to 1.5-year) experimental period of the funded studies. Improved understanding and prediction of factors influencing the hard clam resource can come only with multi-year studies and the maintenance of long-term, decadal-scale monitoring programs. Management strategies, including nutrient management of the watershed to reduce the frequency and intensity of BT, and hard clam stock enhancement to enable or accelerate population recovery, critically depend on such long-term data. The documented high spatial variability in the food supply that promotes clam growth and reproduction, as well as in the occurrence of BT in SSE, provide an opportunity to exploit these habitat differences and optimize the siting of population enhancement efforts. **Continued critical evaluation of ongoing hard clam population enhancement efforts, their goals and cost-effectiveness, is essential.**

Abbreviations Used in this Report

AFDW	Ash-free dry weight
BB	Bellport Bay
BT	Brown tide
Chl <i>a</i>	Chlorophyll <i>a</i>
CR	Clearance rate
DIN	Dissolved inorganic nitrogen
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphorus
DW	Dry weight
GSB	Great South Bay
HCRI	Hard Clam Research Initiative
<i>k</i>	Daily instantaneous growth coefficient
QB	Quantuck Bay
R	Respiration
RE	Retention efficiency
SB	Shinnecock Bay
SL	Shell length
SSE	South shore estuaries
SSR	Spawning stock-recruit
TSS	Total suspended solids
WW	Wet weight

Final Conclusions and Recommendations

Specific conclusions and recommendations for management of hard clam populations as well as future research needs were included in each relevant section of this report, and major research outcomes boldfaced throughout. Key conclusions and recommendations derived from integration of all HCRI studies by the author of this report, with input from HCRI participants, however, are highlighted below.

The earlier decline of hard clam populations in GSB through the early 1980s has been clearly established to be caused by overfishing (Buckner 1984, Kraeuter et al. 2008). Other factors appear to have contributed to their continued decline once fishing pressure was markedly reduced. Model simulations showed that the number of recruits per adult consistently remained below the long-term average starting in 1996, and the period between 1994 and 2001 was marked by the reoccurrence of intense brown tide outbreaks, at levels that in most years exceeded the *A. anophagefferens* densities that are detrimental to hard clam early life history stages (larvae and juveniles). The period 2002-2006, however, was marked by a waning of these blooms in SSE, yet hard clam populations have not rebounded. While model simulations predicted a long recovery period from overfishing for *M. mercenaria* natural populations in GSB (a decade or more) without intervention, **BT and other factors (e.g. low fecundities due to poor food quality and/or poor fertilization success resulting from low clam densities) or a combination of these, may be contributing to the delayed recovery and low standing stock during the past two decades.**

There is a clear need to continue long-term monitoring of environmental data and clam populations. Without such long-term surveys, the efficacy of the hard clam model could not have been evaluated. They are required for further fine-tuning of the model where predictions do not match observations, and proved valuable in the interpretation of current HCRI results. They are also essential to assess population recovery rates and to identify the environmental changes that may affect this recovery. **Inter-annual variability in temperature and food supply, as well as long-term changes expected as a result of climate change, point to the need for multi-year research studies rather than studies focused on a single year.** The role of predators could at present be evaluated only in a cursory fashion, due to the lack of data on the abundance of major predators, including large, mobile predators such as blue crabs, and those that have experienced a latitudinal shift in their distributions (e.g. green crabs). A better knowledge of the predator field is key to the success of restoration efforts conducted in the absence of predator protection.

The spawner-recruit relationship (SSR) for *Mercenaria mercenaria* was based on limited data, primarily at the upper end of the curve, and was therefore associated with considerable uncertainty at higher stock levels (sec. 2). Continued, long-term monitoring is also required to better describe this relationship for Long Island SSE. The relationship developed to date is, however, fairly robust at the lower end of the SSE curve, and predicts that at an average density of ~ 0.7 clams m^{-2} the hard clam population will have difficulty recovering. Clams are known to exhibit an aggregated distribution (Fig. 26, see clam spatial distributions in Islip Town waters between 1992 and 2003 [Polyakov et al. 2007]). The mean clam density data used to develop the SSR relationship were derived from these naturally occurring, non-uniform clam distributions and were used for predictive purposes, yet the error around the mean and the spatial distributions from which it was calculated are of critical biological relevance. It is important to note that even at the threshold mean density at which recruitment is predicted to be near zero (~ 0.7 - 0.8 clams per m^2), fertilization success and recruitment may be restricted to localized patches of highest clam density. **Therefore, additional empirical and modeling data are needed on the clam densities that limit fertilization success, and the effects of spatial and year-to-year variability of clam distribution patterns on recruitment success. The finding of a density-dependent effect on recruitment at low clam densities despite the characteristic high-fecundity of *M. mercenaria*, combined with the relatively low fecundities determined by Newell et al. (2009) for GSB clams in 2001 (sec. 3.1) suggest that fertilization success could be compromised at present low population densities.**

Limited information is available on the quality of the larvae produced in these bays. Studies of gamete and larval quality and clam fertilization success at low population densities are thus needed to determine their effect on hard clam reproductive success. The potential contribution of late summer-fall spawning to hard clam larval recruitment, especially in BT years, is also unknown. Similarly, very little is known about post-metamorphosis survival under natural conditions and its role in limiting recruitment under current environmental conditions. Coupling of the larval hard clam model with that on the population dynamics of juveniles and adults could be used to simulate these effects. HCRI research also suggested that the fall condition of adults may affect reproductive success in the subsequent year, a finding supported by recent data on spawner transplants into GSB (sec. 3.2).

A recurring theme throughout this report is that food quality (e.g. as defined by biochemical composition, species composition, size structure of the phytoplankton and alternate food sources) is a critical factor affecting larval and juvenile clam growth, and adult reproduction. This was generally found to be more important than total food

concentration, as measured by either Chl *a*, organic carbon or nitrogen. Total Chl *a* was repeatedly found in the HCRI studies to be a poor predictor of the food supply for hard clams. Summer Chl *a* levels during BT years in SSE remain within normal levels (~10 to 25 $\mu\text{g L}^{-1}$ described for these bays prior to the occurrence of BT) and would thus not indicate a poor food supply (Cosper et al. 1987). Model simulations confirmed that Chl *a* alone was inadequate to support hard clam growth, and required introduction of a non-algal food supplement to describe the food supply. **Therefore further characterization of both the algal and non-algal food supply, especially for early life history stages (larvae and juveniles) is needed.** Food requirements to support a high reproductive effort of adult clams should also be determined.

At a minimum, size-fractionated Chl *a* could be incorporated into long-term monitoring efforts, since the HCRI demonstrates its utility in providing improved characterization of the food supply for hard clams. Phytoplankton species composition provides a very useful additional level of resolution, as dinoflagellates (Weiss et al. 2007) and pennate diatoms (Streck 2003) were found to be negatively correlated with juvenile hard clam growth. Furthermore, habitat suitability within GSB, and across SSE, to support clam growth and reproduction, was found to vary greatly along spatial gradients. Therefore, it is important to provide adequate spatial as well as temporal characterization of environmental variables affecting clam production. Adult reproductive output (Fig. 17), adult condition index (Weiss et al. 2007), juvenile growth rates and clam densities (Fig. 26) were all higher in Shinnecock Bay than in GSB. The former is also less prone to BT outbreaks, although unusually high *A. anophagefferens* concentrations (up to 480,000 cells mL^{-1}) were reported in 2008 (SCDHS records).

Long-term analysis of western GSB from 1976 to 2000 indicated that DIN concentrations have decreased significantly over this period, in relation to the use of municipal sewer systems, and low DIN tends to favor *A. anophagefferens* blooms (Gobler et al. 2005). It has been hypothesized that *A. anophagefferens* is only one of the species that can fill a summer picoalgal niche in SSE during the transition from the spring bloom community of diatoms and dinoflagellates to the summer community dominated by “small forms” (Smayda and Villareal 1989, Sieracki et al. 2004). **Furthermore, several HCRI studies suggest that reduced clam growth and reproductive performance along spatial gradients is associated with the dominance of “small forms” (*A. anophagefferens* and other unidentified species).** Although the nutrient conditions and speciation that favor blooms of *A. anophagefferens* have been studied extensively, those that favor other picoplankters that are also detrimental for hard clam production, are less well known and need to be further investigated. **Changes in nutrient loading practices should be explored as a potential manage-**

ment option to reduce the occurrence of such blooms given that it is well established that human-induced changes in nutrient ratios can cause changes in phytoplankton species composition and that such changes can also be reversed by management of nutrient inputs (Cloern 2001).

The timing and duration of toxic *A. anophagefferens* blooms coincides with the documented main period of spawning and thus larval production of hard clams in GSB during pre-BT years or a year of low BT (sec. 3.1). **Laboratory studies demonstrated that this algal species inhibits feeding and growth of hard clam larvae in a concentration-dependent manner. High densities of BT are therefore expected to cause recruitment failure of larvae under field conditions, if the occurrence of larvae in the plankton coincides with a BT outbreak, although this remains to be demonstrated.** In contrast, non-toxic *A. anophagefferens* at bloom densities (400,000 cells mL^{-1}), can support relatively good growth of juvenile hard clams as well as excellent shell growth of larvae during planktonic development. Model simulations also show that larval growth is very sensitive to the toxicity of *A. anophagefferens* at low densities. **Characterization of the toxicity of *A. anophagefferens* in the field and its variability among years and sites is sorely lacking.** Chemical markers for toxic cells and rapid bioassays are required to quantify cell toxicity. This will help to interpret differences in experimental results between laboratories as well as identify potential temporal and spatial variability in cell toxicity of *A. anophagefferens* in the field. The HCRI study by Newell et al. (2009) on hard clam reproduction did not coincide with a year of intense blooms of *A. anophagefferens*. Therefore, the effects of BT during spring hard clam gonad buildup and June-July spawning remain unknown. The potential contribution of late summer-fall spawning, once BT has subsided, to hard clam larval recruitment during BT years also needs to be investigated.

There is evidence that hard clams at the time when populations in GSB were relatively abundant exerted profound effects via their grazing pressure in this shallow well-mixed ecosystem. During peak abundance it was estimated that hard clams could filter 40% of the GSB volume per day, and that this has been reduced to only 1-2% at present population levels (Kassner 1993). This ability to exert a strong top-down grazing control has led to interest in hard clam stock enhancement efforts with a view towards ecological restoration. **The decline of clam populations and absence of other benthic macrofaunal suspension-feeders to replace them, however, has led to changes in the food web, and a shift to a system in which grazing is no longer controlled by the benthos.** Clam restoration efforts should take into account that habitat suitability for this species may have changed from the time when this bay supported a major commercial fishery. **Integrated measures of habitat suitability for hard clams**

based on a number of parameters need to be developed for these estuaries, and for specific locations within them.

Transplanting of adult hard clams to establish spawner sanctuaries was conducted by the Town of Islip for three decades in GSB with little success (sec. 1). Stocking was conducted with the *M. mercenaria notata* variety that is rare in the native population and allows tracking of transplants. Only chowder clams were planted until 2003, although large littlenecks and cherrystone clams were stocked in 2006 (S. Buckner, pers. comm.). The hard clam model required a reduction in the number of eggs produced per unit weight for large clams to make realistic predictions of annual egg production (Hofmann et al. 2006a). Model simulations also showed that higher food levels were required to initiate a high level of gonad output in larger animals. Thus chowders, despite their low market price, may not be the best candidate for spawner transplants.

Seed plantings to enhance natural recruitment in bays recurrently affected by BT are not recommended, since juveniles are more susceptible to BT effects and predation than larger clams. Planting of cultured seed in areas less prone to BT using predator protection until the clams attain a size refuge from most predators could provide a viable alternative for hard clam population enhancement in areas that support high growth rates. Information from the HCRI can assist in suitable site selection. Ex-

isting and novel aquaculture technologies to mass produce high-performing, high-quality clam seed at reduced cost should therefore be encouraged. Careful selection of broodstock will be necessary and identification of genetically-based differences in clam susceptibility to BT could greatly advance this effort. Facilitation of leasing practices for aquaculture in SSE and proper safeguards to prevent poaching would also help to stimulate these aquaculture efforts. **Thus, rigorous evaluation of ongoing and future practices to restore and enhance hard clam populations continues to be a pressing management need.**

Restoration efforts for hard clams should clearly establish at the onset their goals and expectations, and develop realistic time-frames and cost estimates to achieve these. These goals may vary widely, e.g. overall ecosystem function and health, recovery of a commercial fishery, or other social goals, including the maintenance of a traditional local lifestyle or source of local employment. Restoration efforts generally meet with enthusiastic public support, and therefore are often not scrutinized or evaluated as closely as other less popular interventions (Mann and Powell 2007). **Therefore, rigorous evaluation of proposed restoration activities and of their outcomes is an essential component of science-based management of this resource.** Cost-benefit evaluation of various management options, ranging from hard clam enhancement to habitat improvement, should also be considered.



Photo credits: top row of clam photos: left, right: Cornell Cooperative Extension of Suffolk County.; center: Preston O. Petre courtesy of Journal of Shellfish Research.

Bottom row: photo of fourth generation GSB clammer Rob Hoek by J. Dlhopsky; photo of clam larvae, S. MacQuarrie