

SUSTAINABILITY OF NORTHERN QUAHOGS (= HARD CLAMS) *MERCENARIA MERCENARIA*, LINNAEUS IN RARITAN BAY, NEW JERSEY: ASSESSMENT OF SIZE SPECIFIC GROWTH AND MORTALITY

JOHN N. KRAEUTER,^{1*} GEF FLIMLIN,² MICHAEL J. KENNISH,³ ROBERT MACALUSO⁴
AND JOETTE VIGGIANO⁴

¹Haskin Shellfish Research Laboratory, Institute of Marine and Coastal Science, Rutgers University, Port Norris, New Jersey 08349; ²Rutgers Cooperative Extension, Toms River, New Jersey 08753; ³Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey 08901; ⁴Brookdale Community College, Sandy Hook Field Station, Lincroft, New Jersey 07738

ABSTRACT In 2000, the northern quahog (= hard clams) *Mercenaria mercenaria* population was surveyed in Raritan Bay with the purpose of determining sustainable harvest levels. To complement this population survey, we determined the size-at-age structure and experimentally determined mortality rate and size specific growth of adult clams. Clams of a range of sizes, obtained from the sampling program, were measured, cleaned, and aged by counting growth rings in sectioned shells. Experimental plots were established in the low intertidal zone at two sites in the Raritan/Sandy Hook Bay system. Marked clams of five sizes were planted in three seasons and harvested quarterly. Experimental estimates of mortality and survival were based on collected live and dead individuals and are thus conservative because they do not address the numbers missing. Some of the clams from both sites were removed from the area by predators. Estimated mortality for individuals >25 mm by instantaneous rate yielded a mean of 0.0176. Integrating the size specific information with the size-frequency distribution from field survey yielded an average instantaneous mortality rate of 0.0187. Growth, based on the difference between the mean size planted and the mean size of the same size class retrieved was analyzed with a general ANOVA, and exhibited typical seasonal growth. The smallest size individuals grew faster than larger individuals. Survey data indicated an increasing clam population and increasing harvests. The survey mortality estimates, based on box counts, seem to overestimate losses. Our experimental work suggests adult mortality rates of nearly 2%, but loss of individuals from the plots made computation of exact mortality rates difficult, and 2% probably underestimates adult natural mortality rates. The results indicate that current levels of fishing mortality are sustainable with 3% natural adult mortality, but a natural adult mortality rate just above 5% would reduce the population growth to near zero. This information is important, because there has been interest in establishing additional depuration facilities to take advantage of the clam population and put more people to work. To sustain current levels of harvest, it will be essential to increase population level monitoring activities over time to assure the population is not being over harvested because of slight changes in recruitment or mortality rates.

KEY WORDS: *Mercenaria*, growth, mortality, fishery, hard clam, northern quahog, sustainability, Raritan Bay

INTRODUCTION

Managing any fishery can be a challenge, but without adequate information on stock levels; recruitment; mortality; and fishing effort, management can at best be considered a guess. Knowledge of the life-history biology is essential for development of any fishery management system. It is generally believed that hard clam recruitment (herein considered to be clams >25 mm in shell length) is controlled by interactions between larval supply, post settlement predation, and substrate composition. Experimental evidence from aquaculture, habitat rehabilitation, and ecological studies suggests that predation from various crustacean predators is the chief cause of loss of hard clam seed >1 mm (Carriker 1959, Carriker 1961, Castagna & Kraeuter 1977, Flagg & Malouf 1983, Gibbons 1984, Kraeuter & Castagna 1977, 1985a, 1985b, 1989, MacKenzie 1977, Peterson et al. 1995, Micheli 1997). Little is known about losses of larvae or seed <1 mm, but predation losses are presumed to be significant. For newly settled clams, substrate type is believed to affect predation rates, and sedimentary pH (Green et al. 2004, Ringwood & Keppler 2002) may be important in predation and or energy allocation to shell maintenance. Clams above 15–20 mm shell length reach a size

refuge where they become relatively immune to most crab predation (Arnold 1984, Peterson 1990, Micheli 1995). Predatory losses of hard clams >25 mm shell length can be attributed to gastropods, fish, and birds (Kraeuter & Castagna 1980, Kraeuter 2001). Kennish (1978) has shown that unknown sources of mortality are the chief cause of loss of adult hard clams. These adult losses are highest in summer and winter and lowest in spring and fall. Models developed for the estimation of harvest levels must explicitly account for the size (age) specific loss of adults from natural causes.

Hard clam population numbers and size structure were recently surveyed in the New Jersey portion of Raritan Bay (Celestino 2003) with the purpose of determining sustainable harvest levels. This survey found that the combined population had increased by greater than 58% (an increase of 551 million clams) from the last survey in 1983. Subsequent to the 2000 survey, the hard clam disease, QPX, was found in western portions of Raritan Bay in both the New York and New Jersey. This disease has caused localized mortality, but the extent of the effect on the population is unknown. The survey also provided clams for an ageing study, and recruitment patterns can be inferred from the age/frequency structure of the population. We experimentally determined mortality rate and size specific growth of adult clams in the Raritan Bay system. The age, growth, and mortality aspects of the population, estimated

*Corresponding author. E-mail: kraeuter@hsrl.rutgers.edu

TABLE 1.

χ^2 analysis of independence of three planting dates (spring, summer, and fall) with samples arrayed as the time after planting and season in which the samples were taken. Live, live animals collected; Dead, dead animals collected; Missing, total planted; (those recovered as either Live or Dead). $n = 1500$, Df 8. First number, χ^2 ; second, probability.

Sample Sequence	Animal Status		
	Live	Dead	Missing
Time after planting	16.76 (0.0327)	19.87 (0.0109)	32.18 (0.0001)
Season of sample	18.88 (0.0155)	17.39 (0.0263)	35.93 (0.0000)

from the ageing study and the experiments, form the basis of this paper. They are then used to evaluate various population growth and harvest options.

METHODS

We established experimental plots in the low intertidal zone at two sites in the Raritan/Sandy Hook Bay system: Spermaceti Cove and at the eastern base of the Earle Naval Pier. We assumed that processes affecting growth and mortality in the low intertidal are somewhat representative of the same processes in the subtidal of the Raritan system. Micheli (1996) has shown that short-term survival of hard clams placed in separate habitat types with varying degrees of restraint is affected by the type of experimental manipulation. In addition, the type of loss varied with habitat and means of restraining the clams, indicating that the same type of manipulation had a differing effect depending on where it was used (Micheli 1996). To compare experimental methods, we placed the clams in the field in two types of plots those within a buried fence enclosure and those not enclosed. Fencing has been shown to decrease losses of experimental clams by reducing the numbers of clams in the missing category (Micheli 1996, Peterson & Black 1993). To determine the effect of differing mortality rates of differing age (size) individuals described by Kennish (1978), we color coded size groups of locally collected clams. To determine if there was differential survival based on when an experiment was initiated, we planted clams in three seasons (with the exception

TABLE 2.

Contingency test of independence (χ^2) on spring planted hard clams. Fence = those surrounded by a fence versus those planted loosely (F), Time = season after planting (T), Site = Spermaceti Cove versus Earle Pier (S), Size = initial size class at planting (I). Degrees of freedom; $F \times T = 4$, $F \times S = 1$, $F \times I = 4$, $T \times S = 4$, $T \times I = 16$, $S \times I = 4$. Those χ^2 values marked with an * show a significant difference at the 95% level.

	Live			Dead			Missing		
	Fence	Time	Site	Fence	Time	Site	Fence	Time	Site
Time	1.97			6.50			9.43		
Site	0.26	1.03		0.04	10.79*		0.64	6.93	
Size	0.31	5.37	0.93	2.14	8.44	6.66	0.59	22.65	10.52*

TABLE 3.

Contingency test of independence (χ^2) on summer planted hard clams. Fence = those clams surrounded by a fence versus those planted loosely (F), Time = season after planting (T), Site = Spermaceti Cove versus Earle Pier (S), Size = initial size class at planting. (I) Degrees of freedom = $F \times T = 4$, $F \times S$, I , $F \times I = 4$, $T \times S = 4$, $T \times I = 16$, $S \times I = 4$. Those χ^2 values marked with an * or ** show a significant difference at the 95 or 99 (or greater)% level, respectively.

	Live			Dead			Missing		
	Fence	Time	Site	Fence	Time	Site	Fence	Time	Site
Time	7.98			3.97			11.37*		
Site	2.59	14.25**		0.02	3.17		0.32	12.00*	
Size	1.73	5.55	1.63	4.57	14.22	3.06	3.33	9.49	15.88**

of winter when clams will not dig in) and harvested them quarterly to be sure our data reflected conditions in the bay and not some planting artifact in the experimental design. Lastly, we included a short term (approximately 1 mo) plant/harvest in all three seasons to evaluate short-term loss of individuals and to provide a basis for evaluation of potential handling effects.

Experimental Design

The formal experimental design consists of the following elements.

- Site (2): Raritan Bay—Eastern side of Earle Naval pier, Sandy Hook Bay—Spermaceti Cove
- Planting Season (3): spring, summer, fall
- Size (mm Length) (5): 26–35, 36–45, 46–55, 56–65, >66
- Restraint (2): Fence, None
- Number of plots to be replicated each sample time (5)
- Replications of each size clam within each plot (5)
- Sampling periods (5) One month and quarterly thereafter

All plots were 2 m² in size and contained 25 individuals (12.5 clams m⁻²). This density approximated a dense group of hard clams in many habitats, but was well below a high density aggregation of hard clams. Bay-wide averages for the Raritan/Sandy Hook system were 3.22 clams m⁻² in 1983 (McCloy &

TABLE 4.

Contingency test of independence (χ^2) on summer planted hard clams. Fence = those surrounded by a fence versus those planted loosely (F), Time = season after planting (T), Site = Spermaceti Cove versus Earle Pier (S), Size = initial size category at planting. (I) Degrees of freedom = $F \times T = 4$, $F \times S$, I , $F \times I = 4$, $T \times S = 4$, $T \times I = 16$, $S \times I = 4$. Those χ^2 values marked with an * and ** show a significant difference at the 95 and 99 (or greater)% levels, respectively.

	Live			Dead			Missing		
	Fence	Time	Site	Fence	Time	Site	Fence	Time	Site
Fence									
Time	2.52			7.50*			7.33		
Site	0.34	37.03**		0.09	5.03		0.37	71.37**	
Size	1.14	5.82	8.73	1.46	11.52	8.61	2.25	9.05	2.59

TABLE 5.
Actual difference and percentage change in average growth of hard clams caused by removal of data from individual size classes with negative growth >-0.5 mm.

Size Class (mm)	Difference (mm)	Percentage Change
26–35	0.103	1.46
36–45	0.082	1.26
46–55	0.115	2.59
56–65	0.088	3.20
>65	0.679	63.95

Joseph 1984), and 7.72 clams m^{-2} in 2000 (Celestino 2003). All experimental size classes were represented by five individuals each time, and 50 replicate plots of each for each planting. Thus each planting at each site contained 1,250 clams or 625 clams in fenced plots and 625 in no-fence plots. Fencing (restraint on movement) was constructed from 4-mm mesh vexas netting cut into strips 10 cm high and buried nearly flush with the sediment surface. Corners were held in place by short lengths of reinforcing rod. Corners of all plots that were not fenced were marked by reinforcing rods at the corners. All clams were marked on both valves to identify the size group to which they belong by rinsing the clams in freshwater, drying the valves, and spray painting. All clams from each size group of each plot were sorted into groups of five, measured, and placed in bags numbered to correspond to a field plot.

Field plots were established parallel to the shoreline with rows of five plots extending from the low tide line to off shore. Thus, 10 rows of plots with 0.5 m spacing between plots were established; each plot was randomly assigned a number, and clams were planted by spacing the marked individuals haphazardly throughout the plot and forcing them into the bottom until they were just covered with sediments.

After the first sampling, approximately 1 mo after planting, each seasonal planting was sampled quarterly for one year. Live and dead clams were recovered by raking and hand digging the entire plot until no more clams were found. At the end of each experiment all plots were resampled to be sure no clams were

TABLE 6.
Spring planting at Sites 1 (Spermaceti Cove) and Site 2 (Earle). Average cumulative growth by initial size and date of sampling. (Because of interactions significant differences cannot be denoted). Times are months after deployment.

Time	Size (mm)									
	26–35		36–45		46–55		56–65		>65	
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
1	3.3	3.7	3.5	2.9	0.6	1.8	0.6	0.4	0.2	0.8
3	6.4	4.8	6.4	6.2	2.7	4.2	2.2	1.5	1.0	0.9
6	12.6	11.3	12.7	10.5	4.8	8.1	5.0	3.3	1.5	1.0
9	14.0	12.0	14.3	12.8	5.6	10.1	5.4	3.7	2.2	1.0
12	19.5	15.6	18.2	14.6	8.0	11.1	6.9	5.1	3.0	0.6

missed. All recovered clams were measured in all three dimensions. Chi-square was used to assess numbers recovered live, dead, and missing. Analysis of growth was by fixed-factor 4-way ANOVA with site, season, size, and fence treated as the fixed factors. Chi-square was used to assess numbers recovered live, dead, and missing.

Temperature was recorded continuously with electronic recorders set to measure temperature every 15 min. These recorders were placed on the sediment surface at each site and anchored to the bottom with a stake at the outer corner of the planting array.

Clams representative of the size range in the bay were haphazardly collected in conjunction with the population survey (Celestino 2003), but an effort was made to assure that all areas of the system and all sizes were represented. These clams were returned to shore, measured, the meat removed, and both valves labeled. A section was cut across the height of the clam, from the umbo to ventral margin along the growth axis (Kennish et al. 1980). One side of this section was polished and then growth rings were counted to establish the age of the clam. No measurements were made on clams older than 10 y of age.

Survival and Mortality

The planted clams were harvested, and all clams found in the plot (live and dead) were enumerated and assigned to the size class in which they were planted by observing the presence of a color. There was no evidence that marked clams had completely lost their coloring; therefore, we assumed that any clam without marks was a native clam. These native clams were enumerated and measured, but not used in subsequent analyses. The sampling of marked clams resulted in three categories: live, dead, and missing. Missing clams are those that were not found and thus they could have been missed in sampling, rolled out of the sampling area and when still alive, or were dead and removed from the area. Estimates of mortality and survival are based on collected live and dead individuals and are thus conservative because they do not address the numbers missing. There were some instances when more marked clams were recovered from a plot than had been planted (because of movement) and this resulted in slightly more total clams being analyzed than were planted. In all cases, this was limited to a few individuals and the missing category was used to normalize the data.

All data from all plantings were combined and tested by contingency tests of independence (χ^2) stepwise comparison of pairs of factors (time after planting, season of sampling, planting season, presence or absence of a fence, site, initial size category) for live, dead, and missing in separate analyses.

Growth

All clams to be placed in the field were placed into 5 size classes based on shell length (26–35, 36–45, 46–55, 56–65 and >65 mm) and painted to represent a size class at planting. All clams of each size class were then separated into five groups of five (5 clams of each size class) and assigned a plot number. All clams in each plot were measured in 3 dimensions (length, height, and thickness). When clams were retrieved, they were placed into groups representing the size at planting (based on the color code) and then measured in the same three dimensions. Dead clams

TABLE 7.

Summer planting Sites 1 (Spermaceti Cove) and 2 (Earle). Average growth by initial size and time of sampling. Times are months after deployment. Because of significant interactions significant differences cannot be denoted, and Site 2 the analysis is split into plots with a fence (F) and those with no fence (No F).

Time	Size (mm)														
	26–35		36–45		46–55		56–65		>65						
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2					
	F	No F	F	No F	F	No F	F	No F	F	No F					
1	1.2	2.2	1.0	0.9	1.5	0.5	0.6	1.8	0.3	0.3	1.5	0.1	0.6	1.1	0.8
3	3.3	3.7	7.0	4.9	6.5	4.7	4.4	3.4	2.9	2.1	1.9	1.5	0.7	4.4	2.7
6	4.7	7.4	5.9	4.0	4.2	3.4	4.5	6.4	3.2	2.0	5.3	0.6	1.5	6.9	0.3
9	6.3	11.0	6.8	6.1	5.0	6.3	4.2	6.2	5.8	2.0	2.2	4.0	1.6	0.5	1.9
12	12.5	9.0	8.0	13.9	16.6	12.5	10.8	10.3	9.0	6.0	4.8	3.9	4.8	0.4	2.8

were measured in the same manner unless valves were missing or broken so thickness could not be measured.

Because clams were not individually numbered, initial size was based on the mean of the five individuals of the original size class that were placed in the field. Similarly, the final size represented the mean size of all surviving individuals in the original age class in the particular plot. Growth was thus based on the difference between the final average size of individuals of a specific size class minus the initial average size of the individuals in that class initially placed in the plot. This method yielded some negative growth rates, because little growth may have taken place (measurement error), and/or a large individual may have died thus reducing the overall mean of a particular size class in a plot. This latter condition was most important in the largest size class because the upper bound was not established, and there was a greater range in the size of individuals in this size class. In larger sizes, large negative values could cause substantial reduction in estimated growth rate. To prevent this, we removed all negative data, except the negatives from 0 to -0.5 mm, because these may represent measurement errors.

All growth data were analyzed by the GLM ANOVA package in Statistix 8 software. The data were grouped by; time after planting, season of sampling, planting season, fence presence or absence, site, and initial size category. In addition, all growth rates were grouped by time of planting, site, and size at planting.

RESULTS

Temperature

Temperature fluctuated seasonally at both sites with maximum high temperatures in the 32°C to 34°C range during low tides in the summer and lows in the -1°C to -5°C range in the extreme of winter. Daily variation ranged from 2°C to over 16°C (midday summer low spring tides).

Survival and Mortality

We know that some of the clams from both sites were removed from the area by various predators, and, in the case of Earle, avian predators carried a substantial number of clams to the nearby pier. Evidence of this behavior was the presence of

colored clam shells on the pier, but we have no mechanism for assigning these clams to a particular plot, and these were not accounted for except as missing individuals. These losses make our estimates of mortality based on dead individuals the most conservative available.

The first test determined if differences existed in the numbers of live, dead, and missing associated with the season in which they were planted. All three categories (live, dead, and missing) exhibited significant differences when analyzed for time after planting and season of sampling (Table 1). The data of the three planting times were then separated for individual analysis, and, because within a planting date, season was not a variable (only one sample set was available for each season), it was not analyzed further.

Spring Planting

Contingency tests of independence (χ^2) were completed based on stepwise comparison of two of the factors (site, fence presence or absence, time after planting, and initial size category) for live, dead, and missing individuals in separate analyses. The only significant comparisons were for site \times time and site \times size (Table 2) for dead and missing individuals, respectively. Because of the interactions, the sites were analyzed separately. These detailed analyses are provided in Appendix 1. Data on spring planting, along with similar detail for summer

TABLE 8.

Average growth (mm) of 5 size classes of hard clams planted in plots in the fall and sampled in 1 mo and quarterly thereafter. Groups with similar superscripts are statistically equivalent. Times are months after deployment.

Time	Growth (Length in mm)				
	26–35	36–45	46–55	56–65	>65
1	0.5 ^{j,k}	0.0 ^k	0.0 ^k	0.1 ^k	0.0 ^k
3	0.9 ^{i,j,k}	0.2 ^k	0.3 ^{i,k}	0.1 ^k	1.1 ^{i,j,k}
6	3.3 ^{f,g}	2.8 ^{g,h}	2.2 ^{g,h,i}	2.2 ^{g,h,i}	1.2 ^{i,j,k}
9	7.3 ^{b,c}	6.0 ^{c,d}	5.1 ^{d,e}	4.6 ^{e,f}	1.8 ^{h,i,j}
12	13.6 ^a	8.7 ^b	7.6 ^b	5.4 ^{d,e}	2.8 ^{g,h}

TABLE 9.
Average annual growth of hard clams in Raritan and Sandy Hook bays by initial size class. Groups with similar superscripts are statistically equivalent.

	Initial Size Category (mm)				
	26–35	36–45	46–55	56–65	>65
Average growth in Length (mm)	14.1 ^a	13.0 ^a	9.1 ^b	5.6 ^c	2.8 ^d

and fall plantings have been separated to provide a clearer summary of general trends.

Summer Planting

There were no significant differences in χ^2 contingency tests for independence for dead individuals in the summer planting (Table 3). Site and time were not independent for live or missing individuals (Table 3) and missing individuals showed additional interactions between time and fence and site and size. With the exception of the missing individuals, there was independence between the site \times fence comparisons for the summer planted individuals (Table 3). There were significant differences between the sites for live and missing clams ($\chi^2 = 78.98^{***}$ and 161.53^{***} , respectively), and for Earle there were differences in live and missing clams ($\chi^2 = 5.82^*$ and 6.96^{**} , respectively) because of the presence or absence of a fence. The data from Spermaceti Cove were then analyzed as a group, and those from Earle were separated by the presence or absence of a fence and then analyzed (Appendix 1).

Fall Planting

Significant lack of independence occurred between the sites (Table 4) for time of sampling and site (live, missing), and for time of sampling and a fence for dead. Because time and site effects were the strongest, we first separated the analysis based on sites. There were time \times fence effects at the Spermaceti Cove site for dead and missing clams ($\chi^2 = 11.00^{**}$, $\chi^2 = 16.82^{**}$,

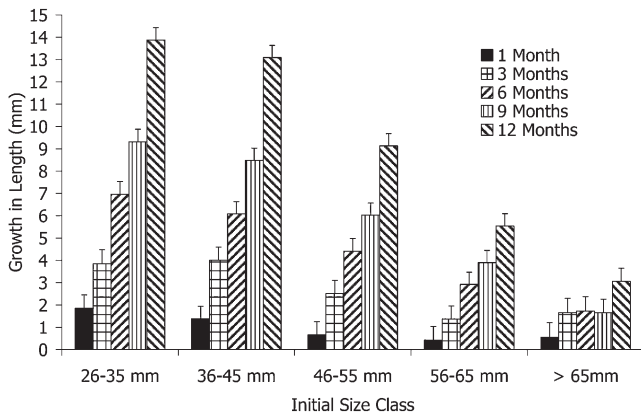


Figure 1. Average growth in length of hard clams, *Mercenaria mercenaria*, planted in the intertidal zone of Sandy Hook Bay, NJ. Initial size class = size range of clams planted. Month = months elapsed from planting to sampling. Error bars are 95% confidence limits.

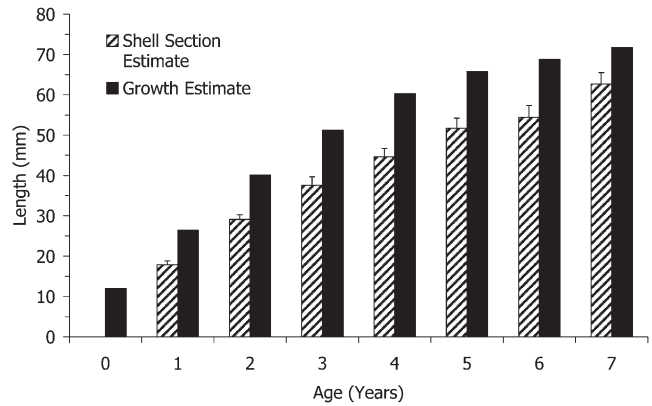


Figure 2. Comparison of size-at-age estimated from shell sections and estimates based on growth of planted hard clams in Raritan Bay, NJ. Size is shell length. Error bars are 95% confidence limits.

respectively), but not at Earle. We separated the first site into fence and no fence groups, but we restricted the analysis of the Earle site to time and initial size. These analyses are provided in Appendix 1.

Growth

Growth information based on the difference between the mean size planted in a plot and the mean size of the clams from the same size class retrieved (with negative growth >-0.5 mm removed) were analyzed with a general ANOVA. The removal of the negative numbers >-0.5 mm had little effect on the data for the smallest size classes, but a substantial effect on the largest size individuals (Table 5). This change is apparent in the difference and the percentage change of the largest class and this is due primarily to the low growth relative to the size of the individuals and the effects of losing individuals that were larger than the average for the plot.

Overall, for both ANOVA's done on the combined data for seasonal effects and for time after planting, there were highly significant differences in growth caused planting season (and time after planting), and as expected, initial size, but there were

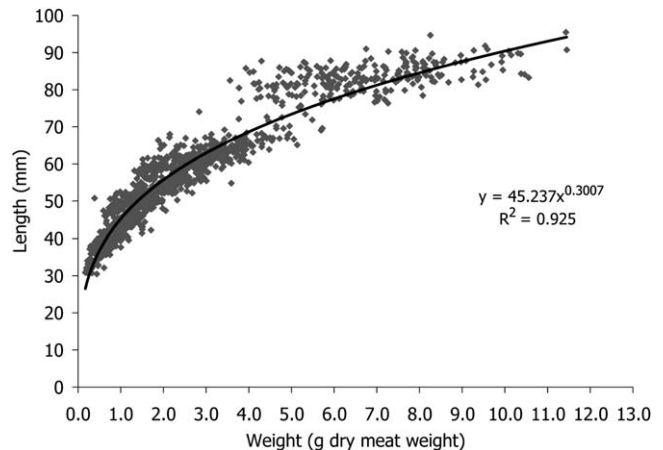


Figure 3. Meat dry weight to shell length relationship for clams planted in the intertidal zone of Raritan Bay, NJ from all size classes planted. $R^2 =$ correlation coefficient.

TABLE 10.

Combined numbers of all size classes recovered live or dead, with missing individuals obtained by subtraction from expected numbers in each plot by time after planting. Percentage of each category (live, dead and missing) based on the numbers recovered or estimated.

	Months Since Planting				
	1	3	6	9	12
Live	1182	1073	1090	1023	983
Dead	27	9	9	9	21
Missing	291	418	401	468	496
% Live	78.8	71.5	72.7	68.2	65.5
% Dead	1.8	0.6	0.6	0.6	1.4
% Missing	19.4	27.9	26.7	31.2	33.1

no differences caused by sites or fences. Because average overall growth for each of the planting dates was significantly different from the other two, each seasonal planting was analyzed separately.

Spring Planting

Combined analysis of all data from the spring planting showed no third or fourth order interactions, and no effects of fences, but there were, as expected, interactions between the initial size and the time the clams had been in the field ($P = 0.0006$). Growth at the two sites was significantly different ($P = 0.0043$) and there were site \times time of sampling ($P = 0.0094$) and site \times size ($P = 0.0000$) interactions. The data were separated by site for further analysis.

Spermaceti Cove

Only initial size ($P = 0.0000$), time of sampling ($P = 0.0000$) and their interaction ($P = 0.0000$) were significant. Growth was greatest in the smallest two sizes of clams, followed by the intermediate sizes of clams and lastly the largest size clams (Table 6). Average growth was the least at the first sampling and greatest by the last sampling.

Earle

Significant differences in average growth followed the same pattern and same probabilities as in Spermaceti Cove, but except for the 46–55 mm size class, total growth at the last sampling was equal to or less than at Spermaceti Cove (Table 6).

Summer Planting

Initial size ($P = 0.0000$), time ($P = 0.0000$) and fence ($P = 0.0056$) and the interactions between size \times time ($P = 0.0000$), fence \times time ($P = 0.0050$) and site \times fence ($P = 0.0231$) were significant. Average growth was greatest in the smallest two size classes, followed by size group 3. There was no difference between the largest two size classes (Table 7). Because of the significant effects caused by fences the data were split between the fence and no fence options for further analysis.

Spermaceti Cove

Within fenced plots significant differences were found with site ($P = 0.0405$), time ($P = 0.0000$), initial size ($P = 0.0000$) and the interaction between time and initial size ($P = 0.0000$). We separated the data by site. There were no effects caused by the presence of a fence in Spermaceti Cove, but time ($P = 0.0000$), initial size ($P = 0.0000$) and their interaction ($P = 0.0000$) indicated significant differences. Average growth by size, site and time after planting are illustrated in Table 7.

Earle

At the Earle site there were significant differences because of the presence or absence of a fence ($P = 0.0024$), initial size ($P = 0.0000$), time ($P = 0.0000$) and the interaction between size and time ($P = 0.0000$). We divided the data between fence and no fence plots, and in both cases the familiar size, time and time \times size interactions were present. Average growth by site, fence presence or absence, size, and time after planting are illustrated in Table 7.

Fall Planting

Average growth from fall planted clams exhibited significant differences in growth based on initial size ($P = 0.0000$), and sampling time ($P = 0.0000$) and their interactions ($P = 0.0000$), but no significant differences caused by site or fence. There were also significant interactions between site and time ($P = 0.0032$). Data are presented for both sites combined (Table 8).

Annual Growth by Size

Because initial size is known to significantly affect growth rates, growth across all plantings for a year growth time and initial size is presented in Table 9. The data show that the two smallest size classes grew at a similar rate and this was closely followed by size class 3. The remaining two size classes grew at significantly different and slower rates (Table 9, Fig. 1).

TABLE 11.

Annual mortality rate for sampling Time after planting 1 = 1 mo, then 3–12 = quarterly samples thereafter. Initial size = initial size range of individuals in 5 size classes. spring, summer, and fall = the time of initiation of the particular group of individuals. * = significantly different from other members of the category.

Time	Spring	Summer	Fall	Average	Initial Size	Spring	Summer	Fall	Average
1	0.0341	0.0292	0.0113	0.0249	26–35	0.0421	0.0028	0.0063	0.0172
3	0.0448	0.0089	0	0.0213	36–45	0.0368	0.0332	0.0025	0.0211
6	0.0193	0	0.0143	0.0126	46–55	0.0342	0.0124	0.0119	0.0223
9	0.0248	0.0116	0	0.0134	56–65	0.0064*	0.0026	0.0079	0.0099
12	0.0261	0.0226	0.0138	0.0186	>65	0.0294	0.0210	0.0108	0.0192

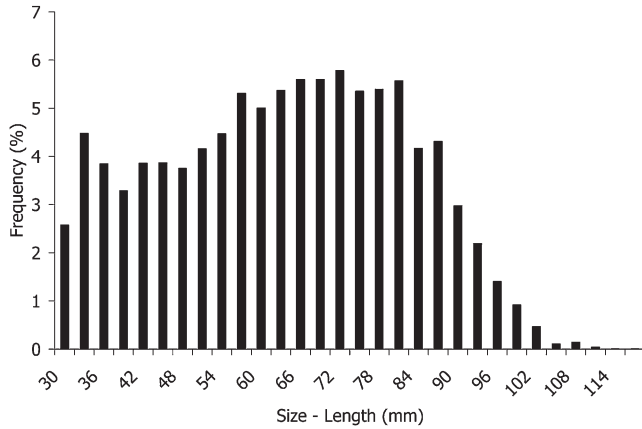


Figure 4. Size-frequency distribution of hard clams, *Mercenaria mercenaria*, collected in Raritan and Sandy Hook Bays in 2000.

We also measured growth by examining growth lines on the shells of individuals collected in the 2000 NJDEP sampling. We examined the growth lines and estimated size-at-age for 539 individuals. These were arrayed in age groups with the media age assigned to the age groups (animals 0–1 y old were assigned age 0.5 etc.) (Fig. 2). Total numbers of animals in each age group were 0.5 = 6; 1.5 = 74; 2.5 = 95; 3/5 = 51; 4.5 = 57; 5.5 = 41; 6.5 = 45; 7.5 = 37; 8.5 = 18; 9.5 = 18; >10 = 97.

Meat Weight

We collected dry meat weight on most live animals sampled during each of the plantings. These data were combined to provide a means of converting clam length to biomass (Fig. 3). Once clams reach approximately 80 mm shell length and about 5 g dry meat weight, the relationship between these two variables begins to lose predictive capability, and meat weight seems to be relatively independent of size. Seasonal effects and/or blunting (thus changing the length/thickness relationship) may be responsible for this change relative to smaller clams.

DISCUSSION

Survival and Mortality

Statistical differences in numbers of individuals were found because of season of planting, sites, fence presence or absence, but primarily because of size at planting and time after planting (Appendix 1). Fence effects were found at Earle, the higher

TABLE 12.

Average seasonal growth of size classes of hard clams in Raritan Bay. Initial size = range in length of individuals planted in each class (mm). Sp = spring, Su = summer, Fl = Fall, Wi = winter.

Initial Size	Sp to Su	Su to Fl	Fl to Wi	Wi to Sp	Total
25–35	4.2	5.5	1.3	3.1	14.1
36–45	5.9	4.4	0.4	2.3	13.0
46–55	3.8	3.0	0.9	1.4	9.1
56–65	2.3	1.7	–0.5	2.1	5.6
>65	1.3	1.1	0.8	–0.4	2.8

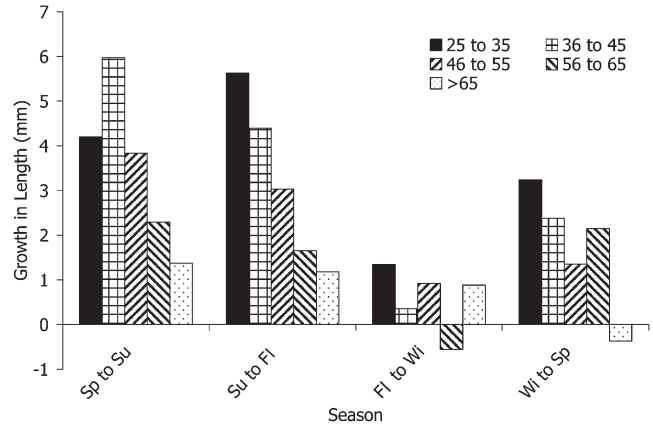


Figure 5. Average seasonal growth in length of various size classes of hard clams, *Mercenaria mercenaria*, planted in the intertidal zone of Sandy Hook Bay, NJ. Size = size range of animals planted. Sp, spring; Su, summer; Fl, fall; Wi, winter. Negative numbers reflect measurement error.

energy site, for the spring and summer plantings, and at the Spermaceti Cove site after the fall planting. In spite of the statistical differences found between the seasonal planting times, sites and occasional fence differences, the dominant factors across all plantings were the time in the field and size of individuals planted. This effect was almost exclusively caused by the relationship between live and missing individuals (Appendix 1). The percentage missing (Table 10) in this study was within the range found by Peterson and Beal (1989) for experimental plots of *M. mercenaria* in North Carolina, where 67% of the plots had 11% to 40% missing individuals.

Because of these losses, and because in most cases the number of dead did not show significant differences with time, we have combined the mortality data. Because the numbers of missing generally increased with time, and dead individuals did not accumulate in the plots, we have used the numbers of live and dead individuals recovered to estimate mortality. Instantaneous mortality rates for live + dead individuals for both time and initial planting size were computed and then converted to the annual rates provided in Table 11. It is probable that actual

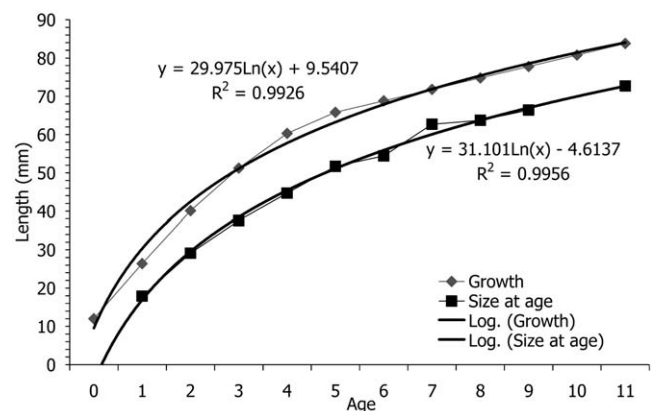


Figure 6. Comparison of size-at-age estimated from shell sections and estimates based on growth of planted hard clams, *Mercenaria mercenaria*, in Raritan Bay, NJ. Size is shell length.

TABLE 13.

Data on Raritan Bay Hard Clam Populations. NJDEP Data from Campbell (1967), McCloy and Joseph (1984), and Celestino (2003). US Public Health data only reported standing stock information. NJDEP mortality estimates from box counts, recruits are those in the 30–37 mm shell length size class. *Data from Kennish (unpublished) back calculated from size-at-age data. ** Data from this report (see above).

	US Public Health Service		NJDEP		Other Data Applied to 83 and 00 Populations	
	1963	1983	2000	1983	2000	2000
Number m ⁻²	5.06	3.22	7.72			
Recruits m ⁻²		0.26	0.70	0.268*	0.642*	
Mortality m ⁻²		0.50	0.67	0.060**	0.144**	
Net gain (loss)		(0.24)	0.03	0.208	0.489	
% Recruits		8.10	9.05	8.32*	8.32*	
% Mortality		15.60	8.45	1.87**	1.87**	
Replacement Time		NA	257 Years	15.5 Years	15.5 Years	

mortality rates were higher, particularly in the smallest size class, but because these individuals were not found, we cannot unequivocally determine their fate.

Examination of the combined data (Table 11) provides some evidence for handling mortality (except for the spring planting, the first sampling has slightly higher, but statistically insignificant, mortality than later samplings), but the data are inconsistent. In addition, dead individuals did not accumulate with time, thus both live and dead clams were being removed from the plots. It is unknown if these processes were linked, but the data suggest they were proceeding at the same rate.

The steady accumulation of missing through time suggests that loss processes were affected by time in the field. About half of the dead clams recovered had chips along the margins suggesting either whelk or crab predation, but a significant portion of all individuals had no discernable marks. This latter condition suggests nonpredation mortality. Subsequent to the 2000 survey, clams in the western portion of Raritan Bay were

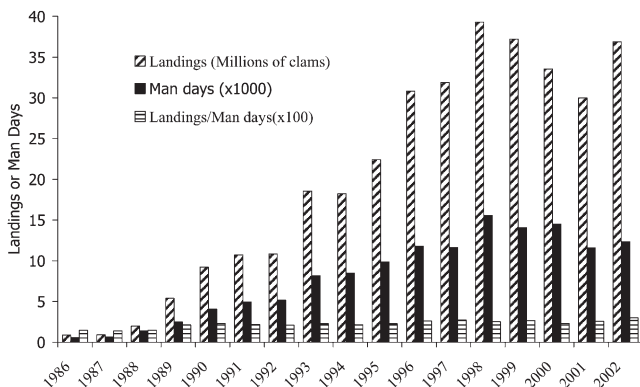


Figure 7. Hard clam, *Mercenaria mercenaria*, landings, effort and catch per unit effort in Raritan and Sandy Hook Bays, 1986 to 2002. Data courtesy of New Jersey Department of Environmental Protection.

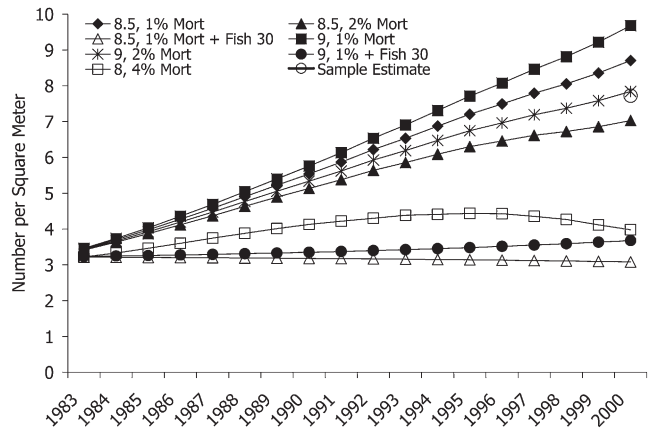


Figure 8. Results of a model utilizing a 1983 hard clam, *Mercenaria mercenaria*, population as a starting point and examining the effects of 8.5 or 9 percent recruitment, a 1%, 2%, or 4% mortality rate (Mort) and fishing mortality as indicated in Figure 7 relative to the 2000 population estimate end point (sample estimate). The Fish 30 data assume that fishing had been removing 30,000,000 clams from 1983 to 2000.

reported to be dying. Analysis showed that they were infected with QPX disease. It is possible that some of the mortality we experienced was caused this disease, but we did not examine any clams for its presence. We did find some of our marked clams at distances from the Earle site on a nearby pier suggesting that bird predation was a significant cause of missing individuals. When hard clams become weak, such as when they are heavily infected with QPX, they are more likely to be found near the surface and as such are more vulnerable to predation. Whether this was the case in the present experiment is unknown, but it would enhance the probability of bird predation in our intertidal locations.

Peterson and Black (1993) reported that a sea star was responsible for the mortality that resulted in the disappearance of the empty shells. No sea stars were seen at our sites. Peterson and Beal (1989) did not analyze mortality rates in their experimental plots in North Carolina, 67% of their missing fell in the 11% to 40% missing range, but there was considerable

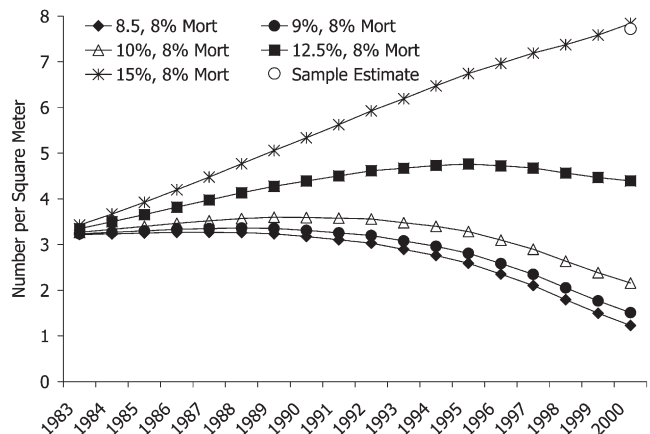


Figure 9. Results of the same model described in Figure 8, but with a constant annual mortality rate of 8%, and a constant recruitment rate varying from 8.5% to 15% and fishing mortality as in Figure 7.

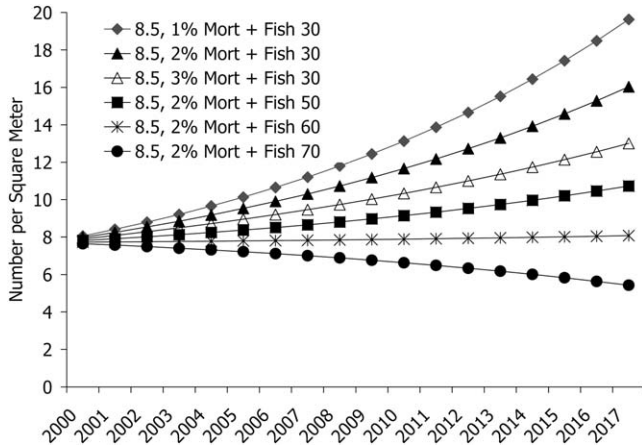


Figure 10. Results of the same model described in Figure 8, but utilizing the 2000 estimated population as a starting point. Recruitment is set at 8.5%, mortality (mort) is 1, 2, or 3%, and fishing at a constant 30, 50, 60, or 70 million clams per year (fish 30, 50, 60, 70).

site-to-site and year-to-year variability even within a site. Simple calculation of population mortality for individuals >25 mm by instantaneous rate for the New Jersey data would yield a mean of 0.0176, but the field population size distribution is not equal in all size classes. Calculation of the same rate utilizing the size distribution from Celestino (2003) (Fig. 4) yields an average mortality of 0.0187. Malinowski (1993) reported on experiments in which 4, 11, 27, and 67 adult (>35 mm shell length) hard clams were placed in replicate 0.33 m² plots for approximately one year. There was no density effect on survival or shell growth although meat displacement volume was significantly less in clams from the highest density plots. Of the 354 clams that were planted, 324 were recovered alive and 14 dead (4.1% mortality). There was no difference in mortality with the size of the animal, but most individuals were in the larger sizes (Malinowski 1993). Examination of size specific mortality in our study also indicates few significant differences because so few dead animals were recovered. Fewer 56–65 mm animals were found dead in

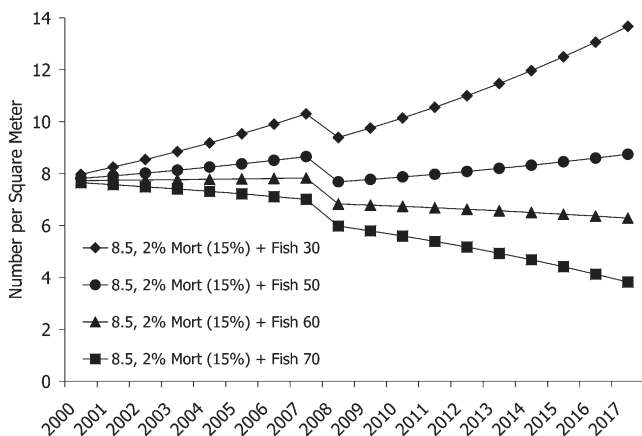


Figure 11. Results of the same model described in Figure 8, but utilizing the 2000 estimated population as a starting point. Recruitment is set at 8.5%, mortality (mort) is 2% and fishing at a constant 30, 50, 60, or 70 million clams per year (fish 30, 50, 60, 70). A 15% one time additional mortality takes place between 2007 and 2008.

TABLE 14.

Numbers of spring planted hard clams recovered live, dead and missing from Spermaceti Cove. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65, and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

Live	Size	T					
	1	151*					
	2	184					
	3	200	**				
	4	222					
	5	223					
	Time	1	3	6	9	12	T
Dead	T	8	0	2	4	4	18
			*				
Missing	Size						
	1	19	**22	11	21	20	93**
	2	19	12	10	7	13	61
	3	4	12	9	7	14	46
	4	5	2	3	7	10	27*
	5	2	3	4	5	11	25*
	T	49	51	37	47	68	156
			*				

the spring sample than expected, and this tendency is also seen in the averaged data, but it is not significant. We do not know if these trends are due only to mortality because we cannot

TABLE 15.

Numbers of spring planted hard clams recovered live, dead and missing from Earle, Fence. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65 and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

A	Time	T					
Live	Size						
	1	77					
	2	106					
	3	100	*				
	4	118					
	5	119					
B	Time	1	3	6	9	12	T
Dead	T	1	5	1	0	3	10
Missing	Size						
	1	15**	3	12*	7	10	47**
	2	2	0	4	5	5	16
	3	3	2	6	6	4	21
	4	0	1	0	4	2	7
	5	0	0	1	1	2	4**
	T	20	6	23	23	23	95
			*				

TABLE 16.

Numbers of spring planted hard clams recovered live, dead and missing from Earle, No Fence. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65, and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

Live	Size	T	Missing	Size	T	Dead	T
	1	77		1	48**		7
	2	104		2	20		
	3	101 *		3	20 **		
	4	116		4	9		
	5	118		5	5*		

preclude differential movement into the missing category by size.

Growth

Peterson and Beal (1989) compared growth of hard clams at differing densities and at different sites in North Carolina. They used fenced and unfenced plots, and there was a significant effect of fencing on growth, but their fences extended above the bottom. In our case the fences were approximately flush with the bottom, and there were no consistent fence effects on growth. Peterson and Beal (1989) used 2 size classes of clams 30 mm and 60 mm, and these approximate our smallest and next to largest size classes. In general, hard clams grow faster in North Carolina than New Jersey because the growing season

TABLE 17.

Numbers of live, dead and missing clams planted in Spermaceti Cove in summer. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65 and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting. A and B see text.

A		Total	Total	Total		
	Initial Size	Live	Dead	Missing		
	1	171	0	79**		
	2	196	3	51		
	3	222 *	1	27 **		
	4	227	1	22*		
	5	210	3	37		
B		Time				
		1	3	6	9	12
Live	Total	212	211	220	199	184
Dead	Total	5	0	0	2	1
				*		
Missing	Total	33	39	30	49	65*
				**		

TABLE 18.

Numbers of summer planted hard clams recovered live, dead and missing from Earle, Fence. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65 and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

	Time	1	3	6	9	12
Live	Total	84*	56	73 **	52	34*
Dead	Total	4	0	0	1	3
Missing	Total	37*	69	52 **	72	88

is slightly longer (Ansell 1968), but our growth rates for these two size classes fall within the range of growth values for both low density fenced and unfenced plots (10 clams m⁻²) reported by Peterson and Beal (1989). These authors noted there was considerable variability in growth between sites and that within some sites there was significant year-to-year variation in growth. Whereas we noted differences in growth caused by the planting time, we cannot determine if this is because of yearly differences or time of planting. Growth patterns in Raritan Bay exhibited typical seasonal growth (Table 12, Fig. 5).

Peterson and Beal (1989) found significant differences in growth at some sites between years, but other sites showed no yearly effects. In Raritan Bay, on a seasonal basis, clams showed the greatest growth from spring to fall and limited or no growth in winter. The intermediate growth in the winter to spring period reflects the late sampling in the spring.

We examined size at age of hard clams collected in Raritan/Sandy Hook Bays during a recent (Celestino 2003) survey of those populations. Kennish (1978) showed that annual growth breaks in the shell of *M. mercenaria* are useful and effective for age and growth determination. Growth cessation in the outer

TABLE 19.

Numbers of summer planted hard clams recovered live, dead and missing from Earle, no Fence. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65 and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

	Time	1	3	6	9	12
Live	Total	103*	57	58 **	74	69
Dead	Total	3	3	0	1	2
Missing	Total	19**	65	67 **	50	54

TABLE 20.

Numbers of fall planted hard clams recovered live, dead and missing from Spermaceti Cove, No Fence. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65 and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

	Time	1	3	6	9	12	T
Live		72	106	98	95	84	455
Dead		3	0	6*	0	0	9 **
Missing	Size						
	1	10	5	8	6	12	41
	2	12	3	6	10	10	41
	3	10	6	1	6	7	30 **
	4	8	4	3	3	3	21
	5	10	1	3	5	4	23*
	T	50*	19	21 **	30	36	156

(prismatic) shell layer caused by physiological response to freezing winter temperatures, for example, generates these deep indentations in the shell. They can also be of value for differentiating between types of mortality in hard clam populations (i.e., natural vs. census or catastrophic mortality) (Kennish 1980). By identifying annual growth breaks in valve cross sections from the umbo to the ventral valve margin, the

absolute age and growth rate of an individual retrieved from a life or death assemblage can be determined. Such growth breaks leave conspicuous, U- or V-shaped notches in the outer shell layer of a clam that can be traced on the external shell surface as concentric linear depressions, or rings. In addition, crossed lamellar shell structure and increased concentration of shell organic matter extend from the inner shell layers to the external shell layer, leaving a dark transgressive band across the shell cross section from the umbo. By counting these bands across the shell from the umbo to the ventral valve margin, the absolute age of the clam can be accurately determined. However, this method of age determination cannot be applied throughout the ontogeny of the organism because many other types of growth breaks develop in the shell as the individual ages, particularly during senescence, and it becomes increasingly difficult to distinguish growth breaks caused by spurious environmental events (e.g., major storms) and physiological stress (e.g., spawning) from annual growth breaks of a cyclical nature. Thus, for this study growth breaks were found to be reliable only for clams <10 y of age.

The size-at-age data (Fig. 2) can be compared with growth data obtained from the current study if the size classes of the current study are considered to represent approximate age groupings (Fig. 2). It is apparent from these data that there is good correspondence between the two estimates for the earliest stages, but the growth estimated from the experimental data is slightly greater than that derived from the size at age data.

The largest size measured by Celestino (2003) was 114 mm. The growth curves, constructed from growth and size-at-age measurements (Fig. 6) yields a 114 mm animal at ages 33 and 46 y old, respectively. Animals reach the littleneck market size at age three to four or four to five for the growth or size-at-age curves, respectively. The size-at-age data may yield older animals of market size because size selection by the fishery crops animals as they reach market size, and leaves slower growing (older) individuals. Year to year variation may also affect the percentage of the recruiting class that reaches market size by a specific size.

Population Changes

One of the primary factors for the development of this study was to provide a basis for the sustainable harvest of the hard clam resources in the Raritan/Sandy Hook Bay system. There have been three major surveys that have examined this clam population. The first complete survey of the area was conducted by the Campbell (1967) based on data collected in 1963. Unfortunately, to date we have been unable to locate the original data; therefore, only information on the mean number of animals is available. NJDEP has subsequently conducted two surveys of the clam population, and these data include both numbers of individuals, estimates of recruitment, and box counts. Based on the information provided in Campbell (1967), McCloy and Joseph (1984), Celestino (2003), the size-at-age data, and the above estimates of survival, we can construct a simple model of the changes in the average hard clam resource in the Raritan/Sandy Hook Bay system from 1983–2000. The available data (Table 13) indicate that since 1983 there has been an increasing clam population and increasing harvests (Fig. 7).

TABLE 21.

Numbers of fall planted hard clams recovered live, dead and missing from Earle. Initial size 1, 2, 3, 4, 5 = 26–35, 36–45, 46–55, 56–65 and >65 mm length. * = 95%, ** = 99% probability. An * before a number indicates a significant difference between that value and others in a column, and an * after a number indicates significant difference between that value and others in a row. The * in the column to the right or below a total column indicates the level of significance for the column or row. T = total. Time = months after planting.

	Time	1	3	6	9	12	T
Initial Size							
Live	1	32	13	17	12	24	98**
	2	46**	22	23	14	17	122
	3	47	29	23	25	27	151 **
	4	49	41	36	28	33	187*
	5	47	32	31	28	28	166
		T	221**	137	130 **	107	129
Dead	T	1	0	0	0	3	4
Missing	1	**18	37	33	38	26	152**
	2	3**	28	27	36	33	127
	3	3**	21	27	25	23	99 **
	4	1**	9	14	22	14	60**
	5	3**	18	19	22	22	84
		T	28**	113	120 **	143**	118

Loss of newly set clams during their first year of life has been found to be the primary factor in controlling natural population levels of most soft sediment organisms including hard clams (Olafsson et al. 1994). Whereas the loss of adult clams is small relative to seed clams, the loss of even a small percentage can have a significant effect on the population of adults available for harvest. For instance, Malinowski (1993) reported that in Rhode Island adult hard clam survivorship ranged from 91.5% to 99.5%, and that survival was independent of the clam density (mean 12.3 m^{-2}). Recruitment into this population was $0.21 \text{ clams m}^{-2} \text{ yr}^{-1}$. Thus in the worst case (91.5% survival) the recruitment of 0.21 clams would not keep up with natural mortality ($1.04 \text{ clams m}^{-2} \text{ yr}^{-1}$). At the other end of the spectrum (99.5% survival) only $0.06 \text{ clams m}^{-2} \text{ yr}^{-1}$ would be lost to natural mortality and recruitment would add to the population. A small (in this case only an 8%) difference in mortality of adult clams can make a substantial difference in the persistence of a given population abundance. This in turn affects those available for harvest.

Hard clam recruitment appears to be relatively low when compared with other bivalve species. This low recruitment means that if a population is over-harvested it will take a substantial period of time for the numbers of individuals to reestablish themselves (Kraeuter et al. 2005). In the Rhode Island case, a $0.21 \text{ clam m}^{-2} \text{ yr}^{-1}$ recruitment rate implies that without any adult mortality it would take a minimum of 58 y to achieve a 12.3 clam m^{-2} population. A recruitment level of between 0 and $0.5 \text{ clams m}^{-2} \text{ yr}^{-1}$ was reported for experimental plots in Barnegat Bay, NJ (Kraeuter et al. 1997), and Kraeuter et al. (2005) reported a range of 0.1–1.06 one-year-old clams $\text{m}^{-2} \text{ yr}^{-1}$ based on 26 y of data from Great South Bay, NY. Kennish (1978), working in Barnegat Bay, found that the average clam lived for <9 y, there was little adult mortality until the clams reach age 5, and then mortality increased with age. It is important that clam mortality rates be established within size (age) classes to correctly model the distribution of those available for harvest.

Estimated Raritan Bay recruitment from all sources fell in the range of 8.1 to 9.1 percent of standing stocks. Mortality was dependant on the type of measure used as an estimator. There is no information on loss of hard clam boxes either through disarticulation or their removal from various types of sediments by currents, predator or other factors. Our data suggest that the processes are important if boxes are to be used for mortality estimates. The NJDEP mortality factors, based on box counts, seem to overestimate mortality. The data presented in this report underestimates adult mortality by some unknown amount (see above for reasons). Data on fishing mortality are available from 1983 to 2000 (Celestino 2003 and personal communication), and because these data result from closely monitored depuration and relay programs they can be considered relatively accurate (Fig. 7).

We have developed a simple model that begins with data from the 1983 sampling and utilizes as constants the estimated recruitment and mortality. Known fishing losses are then used to compare various combinations of these parameters to the 2000 estimated population density (Fig. 8). It is clear that the information can be fit to a simple model of the reported population change, but as little as a 0.5% change in recruitment and/or a 1% change in natural mortality can cause an over or underestimate of the 2000 endpoint.

To test whether a higher level of mortality, such as that from the NJDEP box counts, could still yield the population increase that was observed, we modeled an 8% continuous natural mortality with the observed fishing mortality and then varied the recruitment rate (Fig. 9). A recruitment rate of 15% annually was required to recreate the observed clam population increase. Because none of the three estimates of bay-wide recruitment approach 15%, and because the experimental mortality estimates suggest a rate considerably less than 8%, we focus subsequent analyses on mortality rates of 2% or larger.

Given the span of time between samplings (1983 to 2000) existing data do not allow us to distinguish between an 8.5% and a 9% recruitment rate, and a 1% or 2% natural mortality rate. These results are also sensitive to initial conditions and fishing rate. We compared with the assumption that either an 8.5% or 9% recruitment rate and a 2% natural mortality rate coupled with a continuous 30,000,000 clam harvest each year (Fig. 8), instead of the slow steady increase in harvests that are illustrated by the NJDEP data (Fig. 7), could have affected the final observed 2000 population. These scenarios clearly show that with a modest 2% mortality rate, fishing at 30,000,000 clams beginning in 1983 would have significantly reduced the population recovery.

It is important to emphasize that fishing mortality on this population is constrained by depuration plant limitations, and restrictions on relay. Because of these constraints we estimated future harvests based on constant removals. The use of estimates based on a percentage of the population make models of this type sensitive to the initial conditions. The same combination of recruitment and mortality, when applied to a different starting population can yield substantially different results. Because the existing fishery is working on stocks estimated in 2000, we have used that population level as a starting point (Fig. 10) with a 8.5% recruitment, 1%, 2%, and 3% natural mortality rate and fishing removing 30,000,000 clams annually (Fig. 10). The results indicate this level of fishing mortality is sustainable even with 3% natural mortality. It would take slightly greater than a 5.2% natural mortality rate to reduce the population growth to near zero.

There has been interest in establishing additional depuration facilities to take advantage of the clam population. To evaluate what level of fishing mortality the 2000 population could withstand, we modeled 8.5% recruitment rates with 2% natural mortality with a continuous 50, 60, and 70 million clam fishing mortality (Fig. 10). It seems that under these conditions, this population could yield approximately 60,000,000 clams, slightly less than double what is currently being harvested.

We do not know why the clam population level was lower in 1983 than at present. We do know that harvesting in this system was restricted from 1961 to 1983. To sustain the higher levels of harvest, it will be essential to increase population level monitoring activities to assure the population is not being over harvested because of a slight change in recruitment or mortality rates. To illustrate the effect of a change in the system, we have modeled the 8.5% recruitment, 2% mortality with fishing removing the same 30, 50, 60, and 70 million clams annually (Fig. 11), but we have subject the population to a 15% one-year decline. This one-year decline reduces the population sufficiently that harvest at 60 or 70 million clams annually would cause the population to decline. Given the relatively long

recovery times of hard clam populations (Malinowski 1993, Peterson 2002), it is essential to have adaptive management that can respond quickly to significant population level changes of these stocks. The responses of this population to a one time 15% reduction further emphasizes that if the population is harvested at rates approaching 5% to 7% of the population, surveys will have to be more frequent and management decisions will have to track population changes closely.

We caution that the data we are using from Raritan Bay have double the recruitment rate and half the mortality rate that has been reported by Malinowski (1993) in Narragansett Bay (4.1% mortality and 4.4% recruitment). Rates in Great South Bay, NY were provided by Buckner (1984) (10.7% mortality and 16.8% recruitment), Kennish (1978) did not provide absolute values, but reported high death rates and low recruitment in Barnegat Bay, NJ. Peterson (2002) reported an average recruitment rate of 1.65 m^{-2} , but no data on mortality rates or on natural adult density in North Carolina. Krauter et al. (2005) suggested that in Great South Bay the spawner/recruitment curves suggest a standing stock of around 5 m^{-2} and that this seemed to be typical of many other northeastern populations. Lastly, data from Raritan Bay and other heavily harvested hard clam populations underestimate the effects of illegal activities. It is impossible to tell the extent or importance of these activities, but they are known to be substantial in some areas. We have made the assumption that whatever the effect, it is relatively constant throughout the time period.

APPENDIX 1

Detailed analysis of live, dead, and missing individuals by planting time (spring, summer and fall) by site, presence, or absence of a fence and size.

Spring Planting Spermaceti Cove

At the Spermaceti Cove site, there were significant differences caused by initial size for live ($\chi^2 = 18.31$) and missing ($\chi^2 = 62.26$), but not dead (Table 14). Fewer of the smallest live individuals were found than the larger size classes. Dead and missing individuals exhibited significant differences with time after planting ($\chi^2 = 9.77$ and 9.99 , respectively) (Table 14). Whereas there was a significant time effect on dead individuals, none of the individual time categories were significantly different. Within the missing individual category, there were more of the smallest size individuals and fewer of the largest two size classes missing than expected (Table 14). There were significant differences in missing with time (Table 14), but no particular pattern to the losses.

Earle

At the Earle site, there was a significant lack of heterogeneity in missing individuals because of the presence or absence of a fence ($\chi^2 = 12.26$), and the data were split between fence and no fence groups and analyzed separately. Data for these separated data sets were generally similar to the data for the Spermaceti Cove site in that live individuals only showed significant differences with initial size, but missing individuals showed significant differences with respect to initial size and time after planting (Table 15 Table 16).

Earle Fence

For those clams surrounded by a fence, there were significant differences in live individuals with initial size, but no one size was different from the others (Table 15). There were no differences in dead individuals with size or time. For missing individuals, there were significant differences with both time and initial size. Significant differences were found with time, and there were significantly more individuals of the smallest class missing for the first and third time periods (Table 15). Based on size at planting, more of the smallest and fewer of the largest individuals were missing than expected (Table 15).

Earle No Fence

For those clams not surrounded by a fence, there were significant differences in live individuals with initial size, but no one size was different from the others (Table 16). No differences were found for dead individuals. For missing individuals, there were significant differences with initial size. Across all time periods more small individuals and fewer large individuals were missing than other size classes.

Summer Planting Spermaceti Cove

There were significant differences in the numbers of live ($\chi^2 = 9.84$) and missing ($\chi^2 = 48.43$) clams with respect to the initial size planted at this site (Table 17A). Of the number missing, there were significantly more ($\chi^2 = 29.66$) small individuals missing and fewer ($\chi^2 = 10.40$) size 4 missing than expected. Dead and missing individuals ($\chi^2 = 11.12^*$ and 43.2^{***} , respectively), had significant differences with respect to time (Table 17B). There were significantly more individuals missing at the final sampling ($\chi^2 = 11.00$), than expected.

Earle

Because of significant fence effects ($\chi^2 = 5.82^*$ and 6.93^{**}) for both live and missing individuals, respectively, the data for this site were separated into two classes for analysis: with and without a fence.

Earle Fence

For live, dead and missing clams with a fence there were no significant differences in survival with respect to size at planting. Significant time effects were noted for live and missing individuals ($\chi^2 = 28.03^{**}$ and 24.17^{**}), with more live individuals and fewer missing individuals ($\chi^2 = 9.79^*$ and 11.13^{**}) than expected during the initial sample period, and fewer live than expected ($\chi^2 = 11.13$) during the last sampling (Table 18).

Earle-No Fence

When a fence was absent significant time effects were noted for live and missing individuals ($\chi^2 = 19.41^{**}$ and 29.14^{**}) with more live individuals and fewer missing individuals ($\chi^2 = 13.14^*$ and 20.08^{**}) than expected during the initial sample period (Table 19).

Fall Planting Spermaceti Cove

For the Spermaceti site, there were no effects caused by initial size or time after planting for live, dead, or missing

individuals when a fence was present. When a fence was not present (Table 20), there were no differences in live individuals with respect to initial size or time after planting. There were no differences with respect to initial size in the number of dead individuals found, but there were significantly more dead individuals ($\chi^2 = 9.8^*$) found during the spring sample than at other times. Missing individuals presented a complex picture of significant differences caused by time after planting ($\chi^2 = 19.63^{**}$) and initial size ($\chi^2 = 11.70^{**}$). There were significantly more missing individuals found during the initial sampling period than at later dates, and a general trend of more of the smaller individuals missing than of larger ones (Table 20).

Earle

At the Earle site, there was a significant lack of independence for time after planting and initial size among dead individuals, but this was barely significant at the 95% ($P = 0.046$) level. There were a large number (22 of 25) of 0 observations, so we discounted this result and focused our analysis on time and size at planting. There were more live individuals found during the first sampling than at later samplings, and overall fewer

individuals in the smallest category were found than expected (Table 21). For the entire year of sampling, more 56–65 mm clams were found than expected. Because there were few dead individuals recovered, the missing individual categories are the mirror image of the live individuals. More of the smallest individuals and fewer of the 56–65 mm clams were missing than expected. Within the missing clams, fewer were missing during the first sampling, but more were missing during the winter sampling than expected.

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