2006 Shell-Planting Program in Delaware Bay

Report to the U.S. Army Corps of Engineers

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This report provides information specific to the 2005 and 2006 shell-planting programs. The importance of these programs, for New Jersey, is reviewed in the report of the 9^{th} SAW that is attached to this document as an addendum[⊘]. This is possible because New Jersey carries out a quantitative stock assessment and, as a consequence, can place the recruitment obtained for New Jersey in the context of the quantitative estimates for the native shell on these oyster beds. However, trends in population dynamics are very similar on both sides of the bay, so that generalities concerning the shell-planting program evinced through quantitative methods in New Jersey waters are very likely to be applicable to Delaware waters.

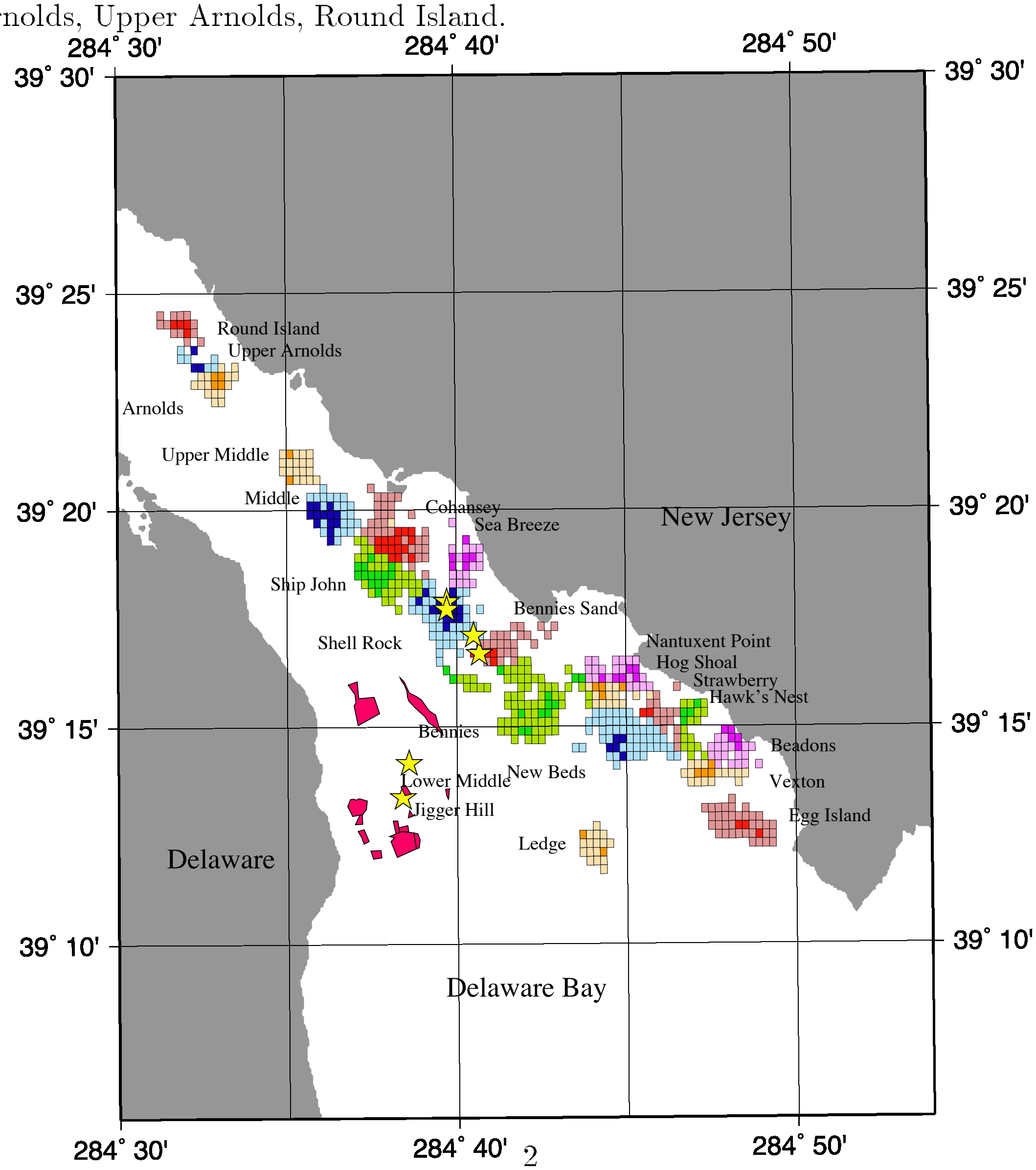
The attached report of the 9^{th} SAW summarizes the status of the New Jersey stock in 2006. Comparison to the Delaware stock survey suggests that similar trends occurred on both sides of the Bay. The 9^{th} SAW found that oyster abundance increased in 2006 from a two-year low that was the lowest abundance level since the onset of Dermo disease circa 1989 and one of the lowest levels in the 1953 to 2006 record. In 2006, abundance was at the 16^{th} percentile of the 1953-2006 time series and the 19^{th} percentile for the post-1988 era. Abundances also rose on the high-mortality beds and on Shell Rock in 2006. See Figure 1 for location of beds and definition of bed groups. The high-mortality beds and Shell Rock ranked at the 18^{th} and 37^{th} percentiles, respectively, for the 54-year time series and at the 25^{th} and 40^{th} percentiles post-1988. Abundance in 2006 on the high-mortality beds rose from 2005, by a factor of 1.29. This is the second consecutive year abundance has increased on these beds. Abundance rose also on Shell Rock, by a factor of 1.67, and for the second consecutive year. The large increase on Shell Rock was partly due to the 2005 shell-planting program.

2006 was the seventh consecutive year of low recruitment in the New Jersey stock. The same seven-year stretch is apparent in the time series for the Delaware

[♮] DRBC, Delaware River Basin Commission; DRBA, Delaware River and Bay Authority; DNREC, Delaware Department of Natural Resources and Environmental Control; NJDEP, New Jersey Department of Environmental Protection; RU, Rutgers University; NJAES, New Jersey Agricultural Experiment Station; HSRL, Haskin Shellfish Research Laboratory

[⊘] HSRL. 2007. Report of the 2007 Stock Assessment Workshop (9^{th} SAW) for the New Jersey Delaware Bay Oyster Beds. 94 pp.

Figure 1. Map of Delaware Bay showing the New Jersey and Delaware oyster beds and the locations of 2005 shell plants, indicated by stars. Note that the Delaware beds are not completely shown, nor is the bed footprint equivalently defined in comparison to New Jersey. The grids on the New Jersey beds represent the $0.2''$ latitude $\times$ $0.2''$ longitude squares used as the template for the New Jersey stock survey. The same areal scale was used on both sides of the bay for shell planting, namely approximately 25 acres or $0.2''$ latitude $\times$ $0.2''$ longitude. For New Jersey beds, the footprint shows the locations of the high-quality (dark shade) and medium-quality (light shade) grids. New Jersey bed groups are defined as follows: High mortality: Beadons, Nantuxent Point, Strawberry, Hog Shoal, Vexton, Hawk's Nest, New Beds, Egg Island, Ledge, Bennies, Bennies Sand; medium mortality (less Shell Rock): Ship John, Cohansey, Sea Breeze, Middle, Upper Middle; low mortality: Arnolds, Upper Arnolds, Round Island.



oyster stock. The number of spat per >20-mm oyster was 0.32; insufficient to sustain the present population. Population dynamics modeling indicates that the market-size component of the population is no longer in a period of negative surplus production, however. Abundance of $\geq 3''$ oysters is expected to increase in 2007, unless fishery exploitation or natural mortality rates‡ are unusually high. Natural mortality accounted for 16.9% of the New Jersey stock in 2006, a relatively high, but still non-epizootic, mortality rate. An increasing trend in Dermo disease suggests that an increase in natural mortality rate can be expected in 2007, possibly reaching epizootic levels.

The 2006 shell-planting program was designed specifically to address the issue of low recruitment and occurred in a timely fashion, as 2006 recruitment on the natural oyster beds again was insufficient to sustain population abundance over the long term. The 2006 program to monitor the 2006 shell plants and the one-year status of the 2005 shell plants was composed of six components: (1) a small monitoring program for a downbay shell plant pursuant to the decision to transplant the spatted shell upbay; (2) a monitoring program to measure spat settlement potential carried out through late September; (3) a monthly monitoring program to track trends in growth and disease exposure for the 2005 and 2006 shell plants; (4) a quantitative evaluation in October to determine the overall success of the project as of season's end in 2006; (5) a dredge calibration component to determine the applicability of remote sampling by oyster dredge of shell plants; and (6) the development of a shell budget to evaluate the effectiveness of the shell-planting program in maintaining habitat integrity.

Summary of Shell-planting Program

The 2005 program consisted of six shell plants in New Jersey and two shell plants in Delaware. The New Jersey program was larger due to the additional support from funds provided by the State of New Jersey; however, as these plants contributed to the program as a whole, they are included in this report. Three types of shell were planted: surf clam shell obtained from New Jersey shucking houses, ocean quahog shell obtained from New Jersey shucking houses, and Maryland oyster shell obtained from shell mining operations in Chesapeake Bay.

Shell planting was carried out in July, 2005. Three 25-acre grids received direct plants in New Jersey: Shell Rock 4, 12, and 43. A fourth plant off Reed's Beach was moved upbay in September to Bennies Sand 11. All three types of shell were planted in New Jersey. Two 25-acre areas were planted in Delaware, on Jigger Hill and Lower Middle beds. Maryland oyster shell was planted in both areas. Ocean

‡ Throughout, the term 'mortality rate' applies to the fraction dying per year. Values given are not true rates; rather, they are equivalent to e^{-mt} in the equation $N_t = N_\circ e^{-mt}$ with m in units of yr^{-1} and $t = 1\,yr$.

quahog shell was also planted on Lower Middle. Specifics of the distribution of shell are provided in Table 1. Locations are provided in Figure 1.

Table 1. Summary of shell-planting activities for 2005. Shell-planting was carried out in July, 2005. Three 25-acre grids received direct plants, Shell Rock 4, 12, and 43. A fourth plant off Reeds Beach was moved upbay in September to Bennies Sand 11. Maryland oyster shell, ocean quahog shell, and surf-clam shell were used. Two harvest projections are shown. The 2005 projection was made at the end of 2005 based on spat counts from that year. Projections of marketable bushels assumed a 3-year time to market size and natural mortality at the juvenile rate in year 1 and at the adult rate in years 2 and 3. The mortality estimates used were the 50^{th} percentiles of the 1989-2005 time series: for Shell Rock, 0.443, 0.182, 0.182; for Bennies Sand: 0.529, 0.267, 0.267. Delaware sites were estimated using Shell Rock mortality rates. Bushel conversions assume 263 oysters per bushel. The 2006 updated projections (right-most column) are based on the observed mortality rates for 2006 (Table 2) and projected mortality rates for years 2 and 3 as above and, therefore, can be considered to be more accurate than those made in the previous year.

Location	Type of Shell Planted	Bushels Planted	Spat Collected	Spat/Bu	2005 Projected Harvest	2006 Projected Harvest
New Jersey						
Benny Sand 11	Replant of surf clam	22,500	12,713,461	565	10,610	20,206
Shell Rock 4	Maryland oyster	36,752	8,051,590	219	10,845	17,952
Shell Rock 12	Ocean quahog	18,248	13,503,520	740	18,189	28,377
Shell Rock 12	Maryland oyster	18,737	2,678,540	143	3,607	5,629
Shell Rock 43	Surf clam	8,000	2,492,214	312	3,356	5,478
Shell Rock 43	Ocean quahog	7,600	3,116,607	410	4,198	6,994
Delaware						
Lower Middle	Maryland oyster	46,382	1,793,637	38	2,415	4,298
Lower Middle	Ocean quahog	17,778	195,037	11	262	467
Jigger Hill	Maryland oyster	54,651	3,122,950	57	4,207	7,039
Total		230,648	47,667,556		57,689	96,440

The Maryland oyster shell proved hard to track as time went on and essentially impossible in year 2. Hence the 2006 status of the 2005 shell plants is determined solely from the clam shell plants.

The 2006 program consisted of eight shell plants in New Jersey and three larger shell plants in Delaware. The total volume of shell planted in New Jersey

Table 2. Observed yearling mortality rates for 2005 shell plants. Data are from monthly counts of new boxes from April to October, 2006. Sampling was not conducted on Delaware sites in May and June. In order to obtain a yearly value, comparable values for New Jersey beds for these two months were applied, Shell Rock 43 for Jigger Hill; Bennies Sand 11 for Lower Middle.

Shell Plant Location	Shell Type Planted	Fraction Dead (yr^{-1})
New Jersey		
Benny Sand 11	Replant of surf clam	0.103
Shell Rock 4	Maryland oyster	0.078
Shell Rock 12	Ocean quahog	0.131
Shell Rock 43	Surf clam	0.091
Shell Rock 43	Ocean quahog	0.072
Delaware		
Lower Middle	Maryland oyster	0.009
Jigger Hill	Maryland oyster	0.068

was higher than Delaware because some additional shell was purchased by New Jersey using matching funds provided by the Bridgeton/Port Norris Empowerment Zone. As these plants contributed to the program as a whole, they are included in this report. Two types of shell were planted: surf clam shell and ocean quahog shell, both obtained from New Jersey shucking houses.

Shell-planting was carried out in June-July, 2006. Six 25-acre grids received direct plants in New Jersey: Hawk's Nest 1, Nantuxent Point 25, Bennies Sand 7, and Shell Rock 20, 24, and 32. Two others were replants, one off Reeds Beach and one off Thompson's Beach. Both were moved upbay in late August to Bennies Sand 6 and 12. Three 25-acre areas were planted in Delaware, on Drum Bed, Silver Bed, and Pleasanton Rock. Specifics of the distribution of shell are provided in Table 3. Locations are provided in Figure 2.

Monitoring of Recruitment and Recruitment Potential

New Jersey carries out a program designed to monitor recruitment potential. In 2006, this program was extended into Delaware waters. Locations are shown in Figure 3. This program records the number of spat settling on 20 oyster valves in deployed bags for consecutive two-week periods at selected sites representative of the natural oyster beds and areas of shell planting in Delaware Bay. The 2006 program showed the anticipated trend of greater spat availability downbay, but a lower setting potential overall than in 2005. The monitoring program suggested that two recruitment waves occurred in 2006, one early, in July, and downbay and another later, in August, and upbay. High settlement potential in the Cape Shore region conforms to the observed higher settlement rates on shell planted in this area and subsequently replanted upbay.

Table 3. Summary of shell-planting activities for 2006. Shell-planting was carried out in late June-early July, 2006. Six 25-acre grids received direct plants, Hawk's Nest 1, Nantuxent Point 25, Bennies Sand 7, and Shell Rock 20, 24, and 32. Two others were replants of shell planted off Reeds Beach and Thompson's Beach and moved upbay in late August to Bennies Sand 6 and 12. Ocean quahog shell and surf-clam shell were used. Projections of marketable bushels assumed a 3-year time to market size and natural mortality at the juvenile rate in year 1 and at the adult rate in years 2 and 3. The mortality estimates used were the 50^{th} percentiles of the 1989-2006 time series: for Shell Rock, 0.451, 0.180, 0.180 for years 1, 2, and 3, respectively; for the remainder: 0.559, 0.252. 0.252. Bushel conversions assume 263 oysters per bushel.

Location		Type of Shell Planted	Bushels Planted	Spat Collected	Spat/Bu	Projected Harvest
Drum Bed		Quahog mix*	49,149	♯0	0	0
Silver Bed		Quahog mix*	82,661	7,646,143	93	10,215
Pleasanton Rock		Quahog mix*	74,474	6,806,179	91	9,093
Hawk's Nest	1	Surf Clam	17,850	3,672,102	206	3,054
Nantuxent	25	Quahog mix*	49,488	10,766,609	218	8,954
Bennies Sand	6	Surf Clam replant	14,811	24,709,636	1668	20,551
Bennies Sand	7	Quahog mix*	49,037	27,669,127	564	23,012
Bennies Sand	12	Surf Clam replant	15,826	43,653,647	2758	36,307
Shell Rock	20	Quahog mix*	48,472	10,330,353	213	13,801
Shell Rock	24	Quahog mix*	53,193	8,030,015	151	10,728
Shell Rock	32	Quahog mix*	23,689	10,859,748	458	14,508
Total			478,650	154,143,559		150,223

*Quahog mix = Quahog and surf clam processed to same small size.

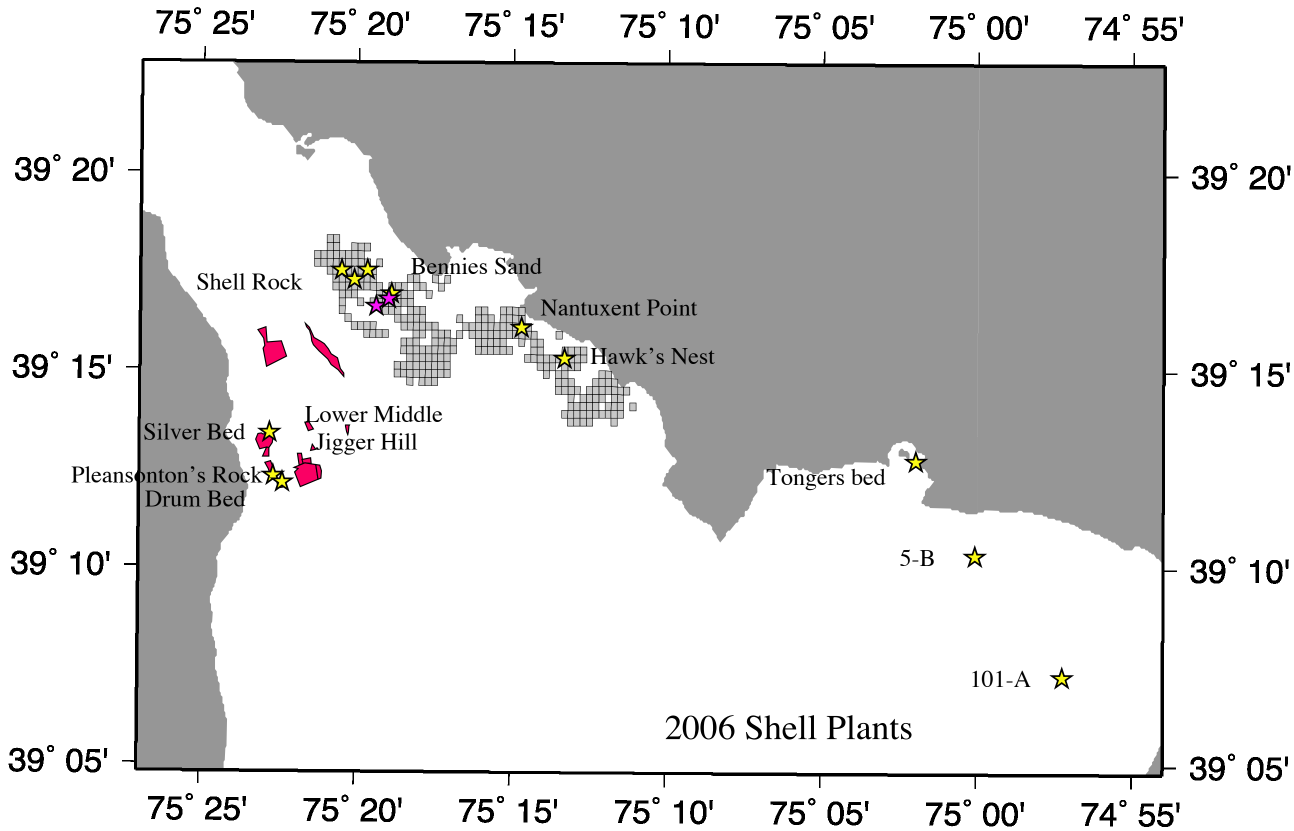
♯Early October sampling by the Dermo monitoring program recovered some spat on this bed; however recruitment was low in comparison to other plants.

Recruitment estimates for 2006 shell plants were obtained from two sampling sources. In October, samples were taken by oyster dredge in survey mode as a component of the oyster stock assessment program. In October, diver samples and closed dredge samples were obtained as a component of the dredge calibration program. Recruitment in 2006 on shell planted in 2005 was only obtained for clam shell plants. These data were obtained during the October stock survey.

Spat sizes at the end of the year generally ranged up to 30 mm. Unlike 2005, a single settlement event produced most the of the spat. Size-frequency distributions were rarely bimodal (Figures 4-7).

In New Jersey, shell was planted directly on the oyster beds and downbay off

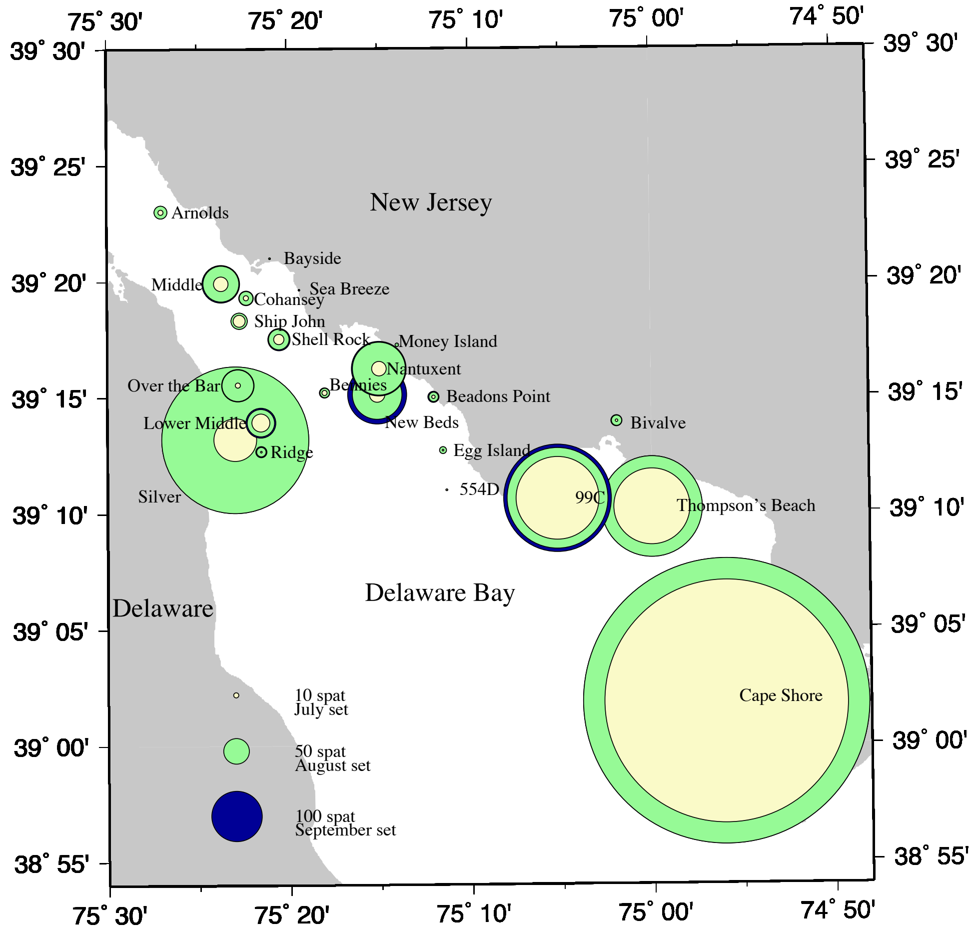
Figure 2. Location of 2006 shell plants, denoted by yellow stars. New Jersey downbay plants are on leased grounds (5-B, 101-A). Transplant locations for these downbay plants are denoted by purple stars. Selected high-quality oyster grounds in New Jersey are denoted by shaded 25-acre grids. Red delineates State of Delaware beds. A complete map of the New Jersey beds is contained in Figure 1.



Cape Shore. These latter plants were replanted upbay. As in 2005, even direct plants significantly out-performed native shell, with an average of 302 spat per bushel. Native shell on Bennies Sand attracted 54 spat per bushel and on Shell Rock, 48 spat per bushel in comparison; thus, the increase in recruitment on directly planted shell was about a factor of 5.9 over native shell. Downbay plants average 2,213 spat per bushel (Table 3). Thus, in contrast to 2005, downbay plants returned more than seven times the spat per bushel of direct plants (Table 3) and about 44 times that of native shell.

Results of the Delaware survey showed that the mean number of spat per bushel of native shell for Silver Bed was 14, for Drum Bed, 7, and for Pleasanton Rock,

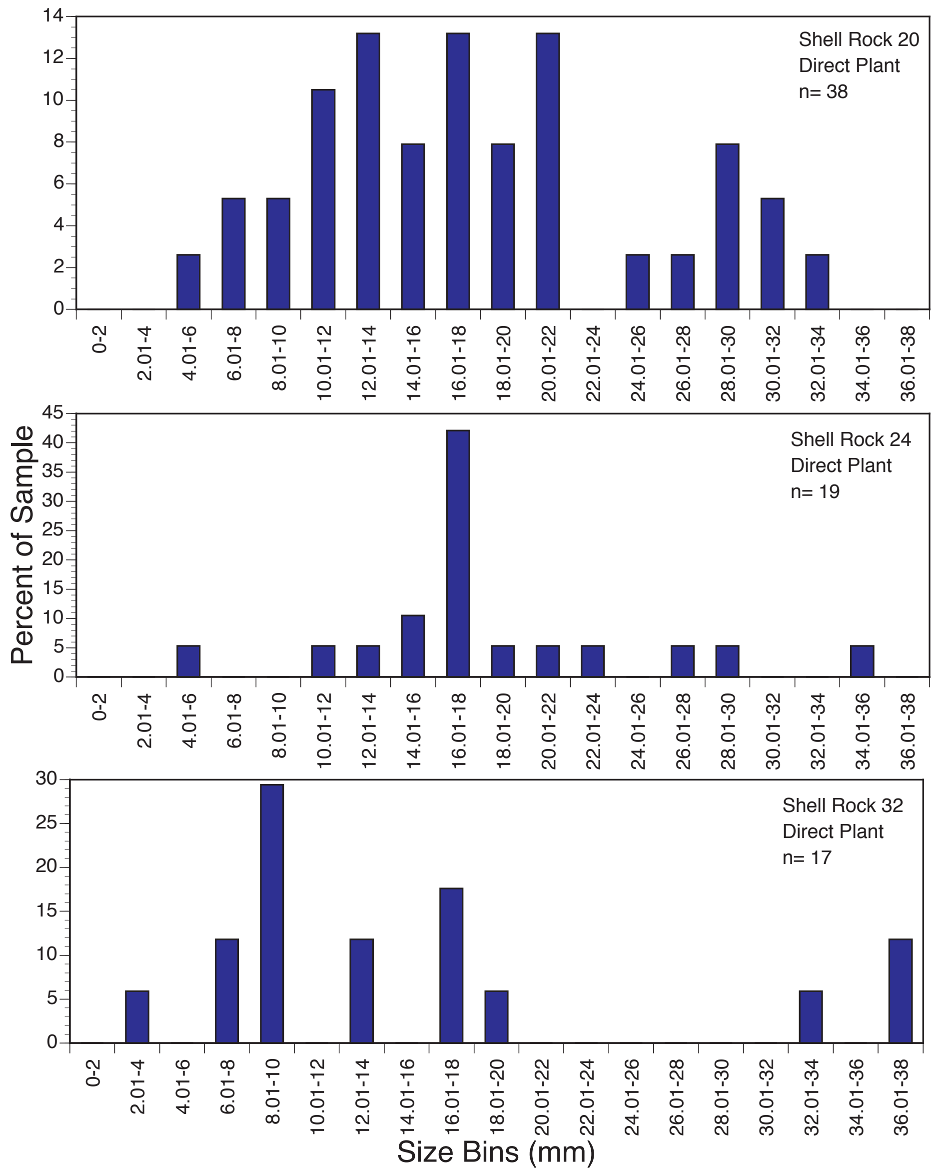
Figure 3. Cumulative number of spat recruiting to 20-oyster-shell bags deployed in the last week of June and collected bi-weekly through September. Colors identify the month of settlement. Increment in circle diameter indicates the number of spat that settled during that time period. Total diameter indicates the cumulative number of spat. Note that circle diameter bears a nonlinear relationship to total spat counts.



9. The values for Silver Bed and Pleasanton Rock for shell plants were 93 and 91, respectively (Table 3), indicating that the planted shell caught considerably more spat than native shell in Delaware as was observed in New Jersey.

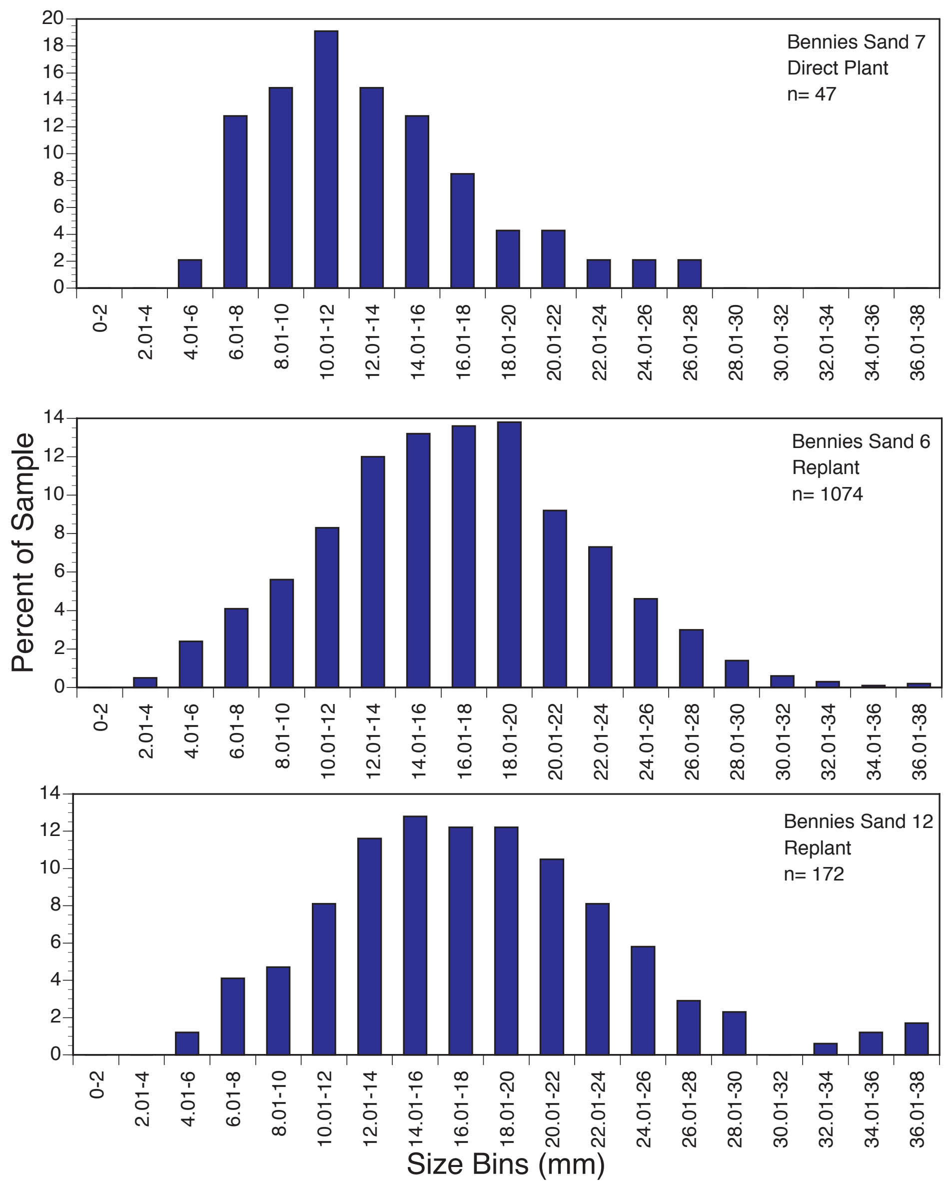
The overall success of recruitment enhancement on a spat-per-planted-bushel basis was better in New Jersey than Delaware. Values in Delaware were around 90 spat per bushel whereas values in New Jersey were in the range of 150-550.

Figure 4. Size-frequency distribution of spat on Shell Rock shell plants.



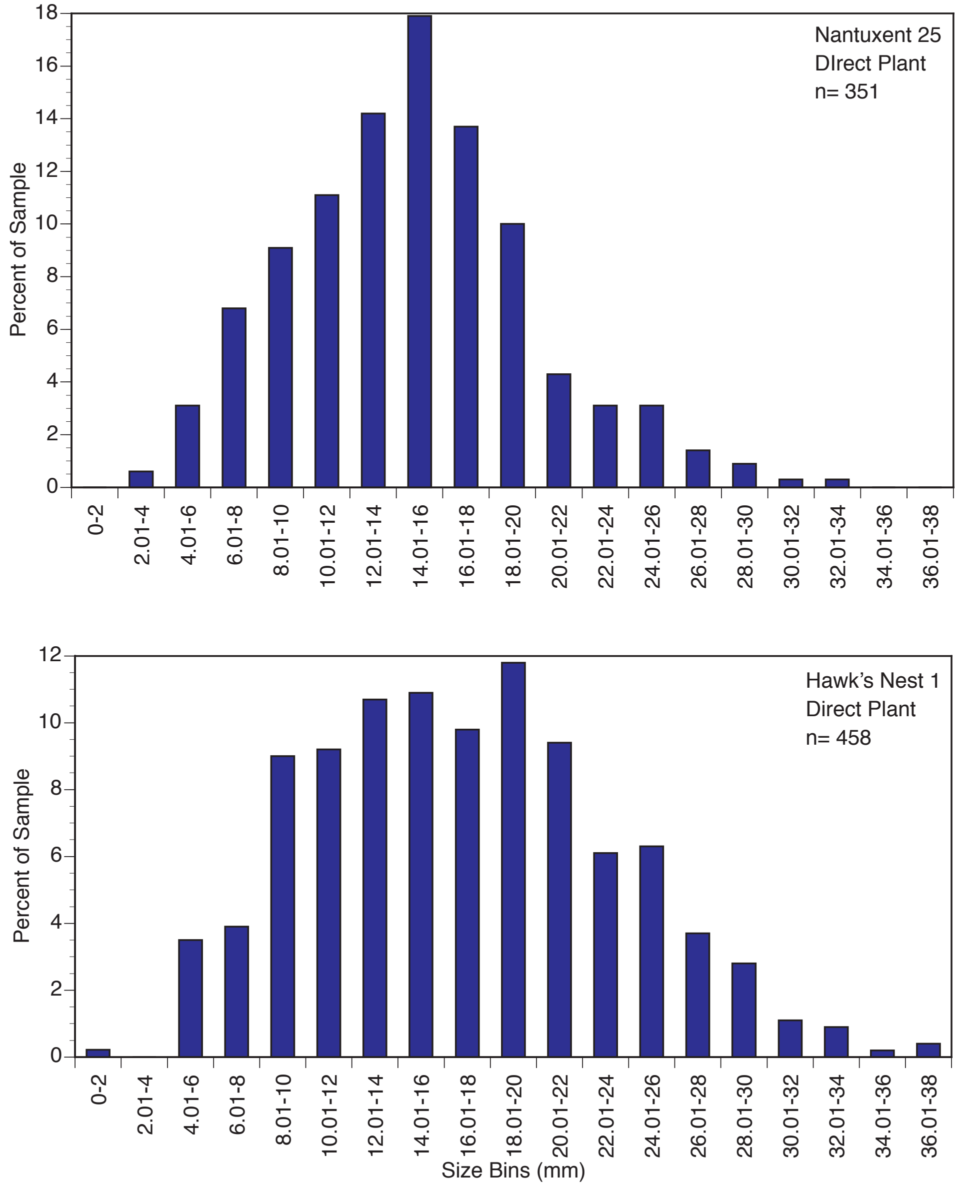
However, recruitment on native shell differed significantly as well. In Delaware, in the areas of the shell plants, values on native shell ranged from 7-14 spat per bushel, whereas in New Jersey, the values were 48-54. Thus both native and planted shell

Figure 5. Size-frequency distribution of spat on Bennies Sand shell plants.



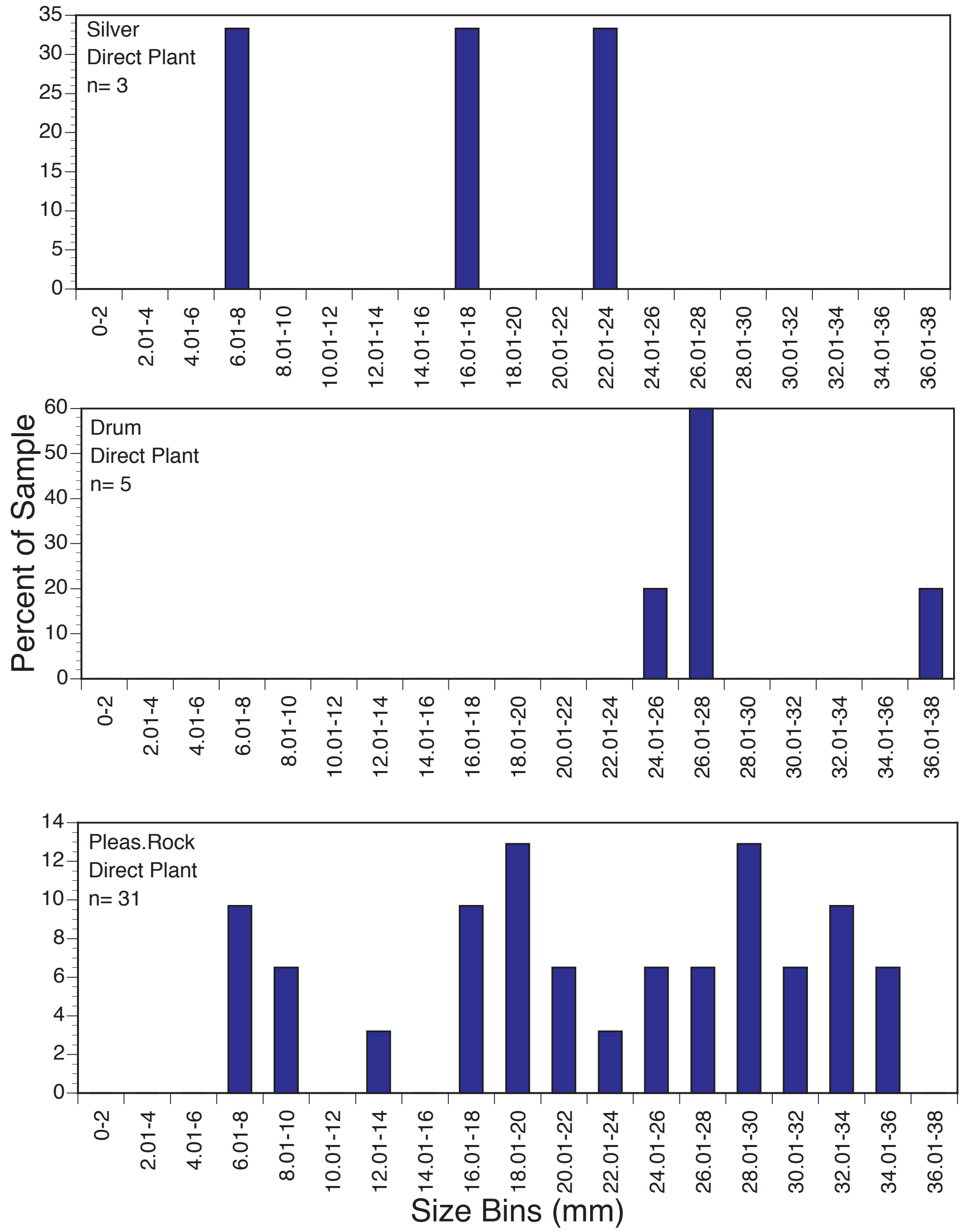
differed by on the order of a factor of 5 between the two sides of the bay in 2006. The differential between the two states would appear to be primarily a function of the greater recruitment potential on the New Jersey side. The same trend was

Figure 6. Size-frequency distribution of spat on Nantuxent Point and Hawk's Nest shell plants.



observed in 2005. As yet, the reason for this gradient in recruitment potential cannot be explained.

Figure 7. Size-frequency distribution of spat on Delaware shell plants.



Overall, recruitment enhancement programs were successful in 2006. In New

Jersey, where quantitative evaluation is easier, shell planting in 2006 enhanced recruitment by a factor of 1.34 bay-wide, providing 26% of total recruitment on New Jersey beds. On Shell Rock, shell plants accounted for 50% of total recruitment. On the high-mortality beds, shell plants accounted for 58% of total recruitment. Spat-per-adult ratios, after including the shell plants, rose to 0.64 on Shell Rock and 1.00 on the high-mortality beds, with percentile positions, respectively, of 50^{th} and 60^{th} for the post-1988 period, in comparison to the ratios of 0.32 and 0.42 on the native shell, respectively, with percentile ranks of 25^{th} and 14^{th}. Spat-per-adult ratios ≥ 1 are desirable because they are always associated with stock expansion. An increase in abundance can be anticipated on Shell Rock and beds downbay in 2007, barring an unusual mortality event or overharvesting.

Downbay Shell Plants

Shell was planted off Reed's Beach in two areas of high setting potential (Figure 2) and then monitored carefully for recruitment. The goal was to transplant this shell back upbay when total recruitment was maximal. As the number of living spat is always a function of the rate of larval settlement and the rate of spat mortality, typically the shell would be moved when spat counts begin to decline. These downbay shell plants were monitored from mid-July until the last two weeks of August, at which time replanting began. This decision was based on the time series of spat counts shown in Table 4, and was constrained by the availability of the suction dredge prior to the last two weeks of August. The end-of-July recruitment event observed in these data is consistent with the results of the spat-bag monitoring program (Figure 3).

Table 4. Time series of spat counts on the downbay shell plants located in Figure 2 prior to their replant upbay in the last two weeks in August.

Sampling Day	Lease 101-5 Spat per Bushel	Lease 5-B Spat per Bushel
July 14	185	0
July 24	370	111
July 30	962	167
August 3	21,669	10,545
August 8	18,697	4,421
August 10	8,010	4,662

Note that the estimates of spat per bushel during the replant (Table 5) fall below the final estimates obtained in October after sampling the upbay site (Table 3). The increment in spat counts is consistent with the later recruitment event upbay that added additional spat to this shell. Note in Figure 5 that these two replants, on Bennies 6 and 12, have spat with an expanded size-frequency distribution relative to that of the direct plant on Bennies 7, supporting the likelihood that the replanted shell continued to attract spat during the later recruitment event after transplanting upbay.

Table 5. Average spat counts of shell replanted upbay from the downbay shell plants located in Figure 2. Shell from lease 101-5 was transplanted upbay on three days in August; transplanting shell from lease 5-B took five days.

Sampling Day	Spat per Bushel
Lease 101-5	
August 15	2,117
August 16	523
August 17	667
Lease 5-B	
August 18	1,527
August 22	851
August 23	1,720
August 28	1,414
August 29	940

Harvest Projections

At the end of 2005, we projected an eventual harvest of 57,689 bushels from the shell-planting program of 2005 (Table 1). The yearly mortality rate† for yearlings from the 2005 shell plants in 2006 was much below the rate typically observed (Table 2). Assuming marketable size is reached in year 3 and that the mortality rate will average at the 50^{th} percentile of the 1989-2006 time series in years 2 and 3 permits a revision of the projected harvest from the 2005 program as shown in Table 1 to a total of 96,440 bushels. The yearlings from these shell plants represent an important source of the abundance increase observed on these beds by the New Jersey survey (see the 2007 SAW report).

Projections of marketable bushels from the 2006 shell plants were obtained by assuming a 3-year time to market size and natural mortality at the juvenile rate in year 1 and at the adult rate in years 2 and 3. The mortality rates used were the 50^{th} percentiles of the 1989-2006 time series: for Shell Rock and Delaware beds, 0.451, 0.180, 0.180, for years 1, 2, and 3, respectively; for Bennies Sand: 0.559,

† The method used is described in: Ford, S.E., M.J. Cummings and E.N. Powell. 2006. Estimating mortality in natural assemblages of oysters. *Estuaries Coasts* 29: 361-374.

0.252, 0.252. 2006 shell plants are expected to provide 150,223 bushels for market in 2009 (Table 3).

The shell planted in 2005 was expected to contribute to the spat set in 2006 also. Only clam shell could be tracked over this period of time. Shell planted in 2005 continued to attract spat in 2006; however the rate of attraction (67/bu) was little better than native shell on the same grids (47/bu). Nevertheless, the net addition of shell to these beds sustained an increased recruitment rate for a second year. Year 2 recruitment will contribute minimally an additional 4,659 marketable bushels in New Jersey in 2009. Because oyster shell primarily was planted in Delaware in 2005 and this shell could not be tracked in year 2, a similar calculation cannot be made for Delaware waters; however a similar outcome is assumed to have occurred.

Monitoring of Growth and Mortality

Perkinsus marinus prevalences in the area of the bay used for shell planting are typically above 50%. In 2006, oysters on the 2005 shell plants were monitored for *P. marinus* infection. Prevalence was lower on the Delaware shell plants, suggesting that disease exposure, as expected, is lower on that side of the bay at a given river-mile marker. Weighted prevalences were substantially lower (Table 6)[∅]. The stock survey conducted by New Jersey obtained bed average infection intensity for October for both Shell Rock and Bennies Sand. Similar data are not available for Jigger Hill and Lower Middle. The bed-average prevalence was 100% and 90% for Shell Rock and Bennies Sand, respectively. These compare closely to the values obtained in October for the animals on the 2005 shell plants (Table 6). The bed-average weighted prevalence was 3.275 and 1.800 for Shell Rock and Bennies Sand, respectively. These values are comparable to the October values for the Bennies Sand shell plant, but substantially above the October values for the Shell Rock shell plants. The evidence suggests that *P. marinus* infection is, if anything, lower on animals obtained from shell plants relatively to animals naturally occurring on the bed and that *P. marinus* infection is lower on the Delaware side. Both suggest that average mortality rates will be below the values used for years 2 and 3 in estimating the number of bushels to be marketed from the 2005 plants (Table 1), assuming overall average mortality rates; that is, the values given in Table 1 are likely to be underestimates.

The 9^{th} SAW determined that Dermo increased in intensity in 2006 over 2005. Although the impact of disease on the animals obtained from shell plants cannot

[∅] Weighted prevalence is based on Mackin's 0-to-5-point scale, where 0 is uninfected and 5 is heavily infected: Ashton-Alcox, K.A., Y. Kim and E.N. Powell. 2006. Chapter 3. *Perkinsus marinus* assay. *In*: Kim, Y., K.A. Ashton-Alcox and E.N. Powell, Eds., Histological techniques for marine bivalve molluscs: Update. *NOAA Tech. Mem.* NOS NCCOS 27:53-64.

Table 6. The prevalence and weighted prevalence of *Perkinsus marinus* in oysters on the shell planted in 2005. ND, not determined.

	Jigger Hill	Lower Middle	Shell Rock 4	Shell Rock 12	Shell Rock 43 ocean quahog	Shell Rock 43 surf clam	Bennies Sand 11
Prevalence							
Jul-06	0.0%	0.0%	5.0%	15.0%	0.0%	0.0%	0.0%
Aug-06	55.0%	40.0%	35.0%	70.0%	20.0%	30.0%	50.0%
Sep-06	40.0%	15.0%	80.0%	90.0%	80.0%	95.0%	75.0%
Oct-06	55.0%	30.0%	80.0%	100.0%	90.0%	95.0%	85.0%
Nov-06	ND	30.0%	100.0%	90.0%	90.0%	95.0%	100.0%
Weighted Prevalence							
Jul-06	0.0	0.0	0.1	0.3	0.0	0.0	0.0
Aug-06	0.4	0.2	0.5	1.0	0.1	0.5	0.7
Sep-06	0.4	0.1	2.3	3.2	2.0	3.1	1.3
Oct-06	0.5	0.3	1.9	1.9	2.1	2.0	1.9
Nov-06	ND	0.6	2.4	2.6	2.5	2.8	3.3

yet be determined fully, the data suggest that an above average exposure will occur in 2007 and that anticipated natural mortality rates will be higher than the long-term average. If this materializes, then the estimated yields in Table 1 will be overestimated because the 50^{th} percentile of natural mortality was applied.

Growth rates were measured for spat that settled on the 2005 shell plants (Tables 7 and 8). These spat averaged about 30 mm in size in March, 2006 and grew to an average of about 40-60 mm by November, 2006. Growth rates were exceptional on Lower Middle and Jigger Hill. In general, growth rates in Delaware waters exceeded those in New Jersey waters. The harvest estimates in Table 1 assume three full years of growth to market size, whereas growth rates shown in Tables 7 and 8 indicate that many of these animals will be marketable prior to the end of year three. Maximum sizes indicate that a fraction of these animals will reach market size in 2007 (Table 8) and that most of the remainder will reach market size within the 2008 season. Thus, these data suggest that the estimated harvests generated by the 2005 shell plants provided in Table 1, already increased relative to year-1 estimates due to low yearling mortality rates, likely remain underestimates.

Shell Budget Projections

A shell budget was constructed using bed-specific half-life estimates for shell[♮].

[♮] Powell, E.N., J.N. Kraeuter and K.A. Ashton-Alcox. 2006. How long does oyster shell last

Table 7. Average size (mm) in 2006 of 2005 spat settled on clam shell planted in 2005. ND, not determined.

	Jigger Hill	Lower Middle	Shell Rock 4	Shell Rock 12	Shell Rock 43 ocean quahog	Shell Rock 43 surf clam	Bennies Sand 11
Sep-05	20.86	16.63	23.67	14.89	18.13	20.04	25.62
Dec-05	18.46	27.30	27.70	ND	25.89	ND	30.38
Mar-06	32.50	26.93	27.34	20.55	29.33	28.27	32.43
Apr-06	32.12	32.46	28.10	23.04	15.93	25.71	26.51
May-06	36.43	35.51	31.82	25.46	27.90	30.36	35.02
Jun-06	40.83	40.59	35.02	31.34	32.91	32.32	38.42
Jul-06	44.73	44.20	39.28	35.76	36.08	35.96	44.01
Aug-06	47.73	43.96	41.46	40.54	36.67	39.04	45.04
Sep-06	53.64	50.30	44.05	43.07	42.11	42.07	47.79
Oct-06	55.50	50.72	42.08	39.09	39.72	45.42	48.95
Nov-06	ND	65.78	ND	39.98	42.14	40.08	49.73

Table 8. Minimum and maximum size (mm) in 2006 of 2005 spat settled on clam shell planted in 2005. ND, not determined.

	Jigger Hill	Lower Middle	Shell Rock 4	Shell Rock 12	Shell Rock 43 ocean quahog	Shell Rock 43 surf clam	Bennies Sand 11
Minimum							
Apr-06	11.60	9.60	ND	5.01	14.85	6.04	ND
May-06	21.61	20.99	19.49	7.24	13.98	7.98	11.14
Jun-06	24.91	24.39	18.17	13.83	15.81	13.96	11.68
Jul-06	25.10	25.31	23.85	18.04	20.51	17.87	19.87
Aug-06	31.91	18.70	23.14	20.00	12.50	16.13	14.68
Maximum							
Apr-06	49.57	52.93	ND	48.60	18.08	51.99	ND
May-06	48.25	50.52	47.52	48.72	42.43	50.26	35.25
Jun-06	50.87	53.22	49.92	47.20	48.76	53.39	54.38
Jul-06	60.93	58.66	58.48	55.91	51.12	66.40	61.83
Aug-06	62.66	64.06	63.09	66.83	55.36	62.85	77.12

Half lives ranged generally between 3 and 10 years (Table 9). The analyses are subject to substantial yearly variations when analyzed retrospectively because not all beds were sampled each year in the first two-thirds of the time series, because the addition of shell beginning in 2004 increases the difficulty of analysis as industry

on an oyster reef? *Estuar. Coast. Shelf Sci.* 69:531-542.

dredging redistributes the shell beyond its original grid placement, and because the half-lives for surf clam and ocean quahog shell may diverge substantively from that for oyster shell. Outlier half-life values occurred on beds poorly sampled in the first two-thirds of the survey or beds heavily impacted by shell planting in 2005-2006. Three beds have negative half-life estimates: Round Island, Upper Middle, and Sea Breeze. All three were surveyed in alternate years from 1996-2003; thus the time series for these beds is inadequate.

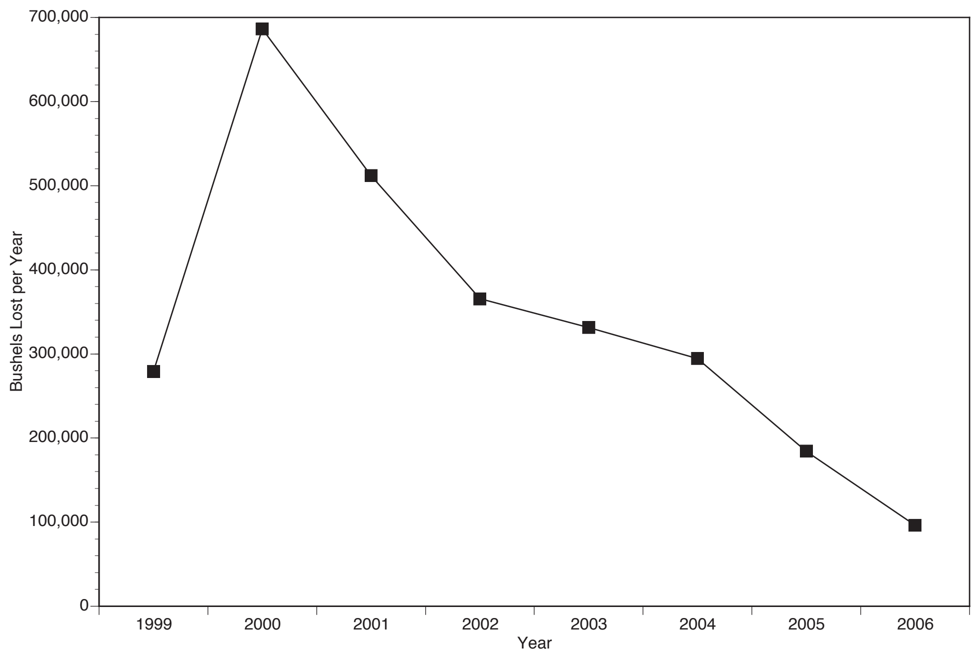
Table 9. Average half-lives for surficial oyster shell on Delaware Bay oyster beds, for the 1999-2006 time period.

Location	Half-life (yr)	Location	Half-life (yr)
Round Island	-5.36	Bennies	5.32
Upper Arnolds	8.28	Nantuxent Point	3.31
Arnolds	4.24	Hog Shoal	4.64
Upper Middle	-1.64	Hawk's Nest	6.20
Middle	7.95	Strawberry	4.28
Cohansey	13.91	New Beds	15.63
Ship John	5.52	Beadons	570.81
Sea Breeze	-78.01	Vexton	6.99
Shell Rock	4.61	Egg Island	8.78
Bennies Sand	55.03	Ledge	9.15

New Jersey oyster beds have been losing on the order of 250,000 to 500,000 bushels of shell annually since 1999 (Figure 8). 1999 is the first year an estimate can be made as 1998 is the first year that full survey data are available. The shell budget shows a substantial reduction in shell loss in 2005 and 2006 as a result of the shell-planting program that has reduced by at least two-thirds the yearly deficit. Similar estimates for Delaware cannot yet be made, as quantitative information on shell content is unknown. However, loss rates observed on Middle, Shell Rock, Ship John and Cohansey are likely indicative of loss rates on Delaware beds, as the location of the Delaware beds in the salinity gradient is similar to the named New Jersey beds.

By region, the low-mortality beds have been losing about 20,000-40,000 bushels annually (Figure 9). This lower level of shell loss is due to low taphonomic loss rates. The medium-mortality beds are losing 30,000 to 100,000 bushels annually due to higher loss rates and larger total area. Shell Rock has shown a net gain since 2005 due to shell planting. The high-mortality beds are losing 175,000 to 350,000 bushels annually due mostly to the larger area of coverage. A reduction in the rate of decline in 2006 is due to the substantial shell planting that occurred downbay of Shell Rock.

Figure 8. Estimated number of bushels of shell lost from the New Jersey oyster beds for the time period 1999-2006. Lower estimates in 2005 and 2006 reflect the addition of shell through shell planting to offset the shell loss.

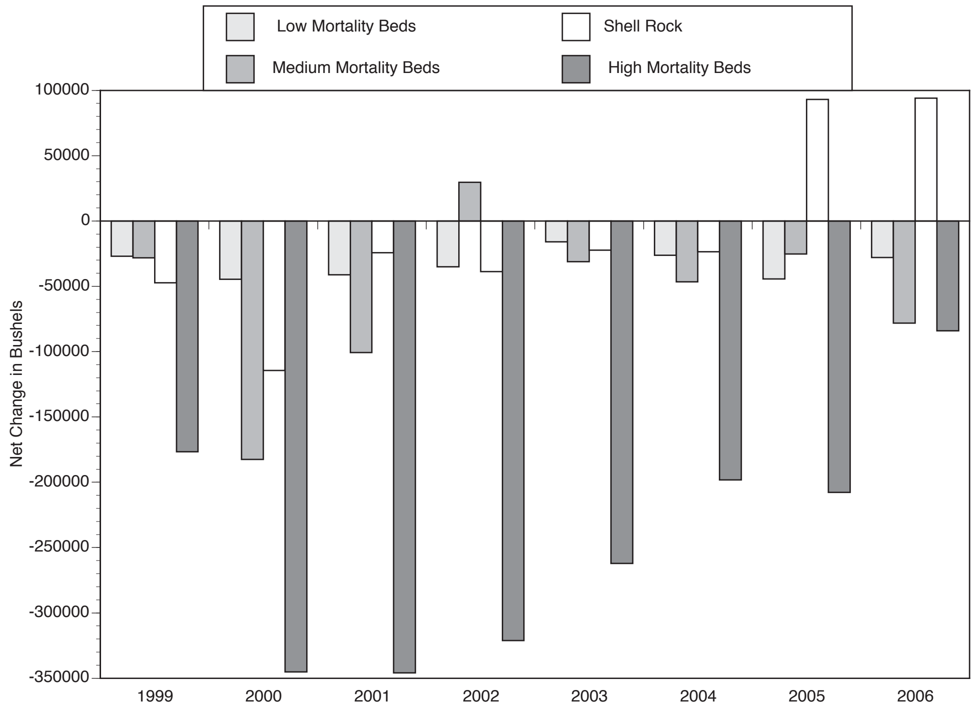


By bed, Ship John and Bennies have the largest negative numbers, Bennies due to its large size and Ship John due to its high loss rate (Table 10). Other beds exceeding a loss of 1 million kg per year include Arnolds, New Beds, Hog Shoal, Vexton, and Egg Island. Four of these beds are high-mortality beds with low abundance and thus low rates of natural shell addition. Five beds had positive balances in 2006; four of these were the beds on which shell planting occurred. The fifth is Beadons.

The shell budget estimates identify the importance of shell planting in maintaining the integrity of the beds during times of disease when low abundance limits the amount of shell added to the beds naturally as animals die. The shell budget also permits more effective planning for future shell plants in New Jersey waters.

Most beds not receiving shell plants in 2006 suffered a loss of surficial shell. Continued shell planting is essential to maintain habitat quality as well as provide substrate to enhance recruitment. Shell plants should target areas where marketable oysters grow but where cultch loss exceeds the addition of shell through natural mortality. The Ship John region is such a case. Due to the enhanced survival of

Figure 9. Estimated net change in surficial shell content in bushels by bay region for the New Jersey oyster beds for the time period 1999-2006. Positive values on Shell Rock in 2005 and 2006 reflect the addition of shell through shell planting to offset the shell loss.



juveniles in this region, replants from downbay plants should be moved to selected areas of Ship John in 2007. This will maximize the return from this more costly endeavor. The same region, and Cohansey as well, have the lowest fraction of small oysters in the size-frequency distribution of any bay region. Hence, these beds also should be considered for direct shell plants in 2007. Downbay plants and replants should be expanded to the extent funds permit to enhance recruitment.

Shell Rock and Bennies Sand should not be planted in 2007.

The high-mortality beds have the fastest growth rates and best oysters for marketing, but increasing abundance in this region increases the risk of epizootics. The shell-planting program should not exclusively target this area; however, Nantuxent Point, Hawk's Nest, Hog Shoal, Vexton, and Strawberry should be considered as planting locales for direct shell plants. Planting should not occur on Bennies and New Beds as evidence indicates that oysters in this region suffer proportionately higher Dermo mortality for a given disease level than the inshore beds (see 2007

Table 10. 2006 shell balance (net change from 2005) for Delaware Bay oyster beds (in kg per bed). Arrows identify locations receiving 2006 shell plants.

Location	Net Change in Shell	
Upper Arnolds	-424,397	
Arnolds	-1,616,357	
Middle	-908,253	
Cohansey	-151,022	
Ship John	-4,670,979	
Shell Rock	6,881,596	⟵
Bennies Sand	6,002,242	⟵
Bennies	-5,638,249	
Nantuxent Point	963,856	⟵
New Beds	-1,154,274	
Hawk's Nest	210,086	⟵
Hog Shoal	-1,863,915	
Strawberry	-858,048	
Beadons	21,264	
Vexton	-1,388,771	
Egg Island	-1,722,509	
Ledge	-733,859	

SAW report).

Dredge Efficiency

A series of experiments to determine dredge efficiencies were again conducted to ascertain the continued reliability of the survey quantification and to evaluate the efficiency of capture of planted shell.

Comprehensive dredge efficiency measurements were conducted on Hawk's Nest and Nantuxent Point. Values for the efficiency of capture of native shell were representative of previous experiments. Live oyster catchability coefficients[♭], q, averaged 3.93 versus the 3.11 value obtained in 2003[⊗]. Boxes averaged 6.01 versus

[♭] The catchability coefficient q as used herein is defined as the inverse of dredge efficiency e: $q = \frac{1}{e}$.

[⊗] 2003 and 2000 values are taken from: Powell, E.N., K.A. Ashton-Alcox, J.A. Dobarro, M. Cummings, and S.E. Banta. 2002. The inherent efficiency of oyster dredges in survey mode. *J. Shellfish Res.* 21:691-695 and Powell, E.N., K.A. Ashton-Alcox, J.N. Kraeuter.

4.64. Cultch averaged 9.05 versus 8.14. These additional measurements suggest that dredge efficiency has changed little since 2003.

In 2005, extensive dredge efficiency assessments revealed that the survey dredges had a low efficiency of capture of surf clam and ocean quahog cultch. Additional information obtained in 2006 confirms this trend (Table 11). In general, surf clam cultch is caught with greater efficiency, albeit still low, than ocean quahog cultch. This is likely a result of the somewhat larger size of the surf clam material. In either case, the data suggest that diver sampling is the most advantageous approach to quantitative assessment of shell plants.

Table 11. Catchability coefficients, calculated as the reciprocal of dredge efficiency, for spat on planted cultch and for planted cultch.

Type of Shell Planted	Spat	Cultch
2005 efficiency values		
Ocean quahog	98.30	197.59
Surf clam	150.25	123.73
2006 efficiency values		
Ocean quahog	238.15	333.09
Surf clam	131.91	112.01

As diver sampling is inherently logistically complex and costly, we evaluated the performance of an oyster dredge with reduced ring size. A standard survey dredge has a bag composed of 50.8 mm rings. A dredge of this type was outfitted with a chain bag lined with a flexible stainless steel mesh of approximately 1/8″ ID to catch the smallest pieces of quahog shell. The the sides were left un-lined to provide sufficient water flow while dredging. Side-by-side measured tows were taken with the standard survey dredge and the closed survey dredge. The closed dredge was normally a factor of 2 to 10 more efficient than the standard dredge (Table 12). In comparison, divers were normally more efficient by a factor of 100 or more. Thus, the closed dredge, although providing an improved sample relative to the standard dredge, did not offer sufficient improvement to obviate the need for divers as a primary sampling tool.

Table 12. Catchability coefficients calculated as the reciprocal of dredge efficiency for the standard survey dredge relative to the closed dredge. –, insufficient data.

in press, Re-evaluation of Eastern oyster dredge efficiency in survey mode: Application in stock assessment. *N. Am. J. Fish. Manage.*

Bed or Bed Group	Year	Shell Type	q for Spat	q for Cultch
Delaware				
Lower Middle	2005	ocean quahog	–	1.76
Drum, Silver, Pleasanton Rock	2006	ocean quahog	–	16.58
		surf clam	5.14	46.89
New Jersey				
Bennies Sand 11	2005	ocean quahog	5.61	3.52
Shell Rock 12,43	2005	surf clam	1.15	0.11
Bennies Sand 6,7,12	2006	ocean quahog	4.25	9.69
Shell Rock 20,24,32, Hawk's Nest, Nantuxent Point	2006	surf clam	2.55	9.99