Horseshoe Crab Spawning Activity in Delaware Bay: 1999 – 2007

Report to the Atlantic States Marine Fisheries Commission's Horseshoe Crab Technical Committee

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Summary

- This marks the ninth year that the Delaware Bay Horseshoe Crab Spawning Survey has been implemented in a standardized manner throughout May and June in the Delaware Bay.
- The survey is completed annually through the assistance and dedication of numerous volunteers and coordinators.
- Estimates of female spawning activity were precise. Annual coefficients of variation were below 14% for the entire series and remained below 10% for the last six years.
- Female spawning activity peaked during the third lunar period sampled (May 30, June 1 & 3). This was similar to 2005.
- In 2007, most of the female spawning occurred in June (58% in DE and 55% in NJ). The percent spawning in May was higher in NJ than DE in each year of the survey.
- Percent of female spawning that occurred in May was associated with water temperature (correlations were 0.75 and 0.76 for DE and NJ, respectively).
- Baywide female spawning activity over the past 9 years remained stable (Slope = 0.01, SE = 0.01, 90% CI = -0.01 to 0.03, P = 0.32).
- No significant trends in state-specific female spawning were detected; though, the slope in Delaware was negative and the slope in New Jersey was positive.
- This year male spawning activity was reported because of the concern over male-only harvest. Estimates of male spawning activity were precise. Annual coefficients of variation were below 20% for the entire series and remained below 10% for the last six years.
- Estimates of baywide male spawning activity showed a significant increase from 1999 through 2007 (Slope = 0.20, SE = 0.04, 90% CI = 0.11 to 0.28, P < 0.01).

Introduction

The Atlantic States Marine Fisheries Commission's (ASMFC) Interstate Fishery Management Plan for Horseshoe Crab (ASMFC 1998) required that the states of Delaware, Maryland and New Jersey implement pilot horseshoe crab spawning surveys based on "standardized and statistically robust methodologies". In January 1999, the ASMFC convened a workshop that established a framework for such surveys in the Mid-Atlantic region. The framework built upon existing horseshoe crab spawning survey efforts by Finn et al. (1991) and Maio (1998). Using funds from the U.S. Geological Survey's (USGS) State Partnership Program, a comprehensive pilot study was designed and implemented in Delaware Bay during the spring of 1999 (Smith et al. 2002). The U.S. Fish and Wildlife Service provided further funding in 2000 to continue the survey in its present form, and the Delaware Division of Fish and Wildlife (DE DFW) provided funding in subsequent years using Atlantic Coastal Fisheries Cooperative Management Act funds. The survey has been shown to provide levels of spatial and temporal coverage essential for understanding trends in spawning activity (Smith and Michels 2006).

The survey is an excellent example of state, federal, non-governmental organization (NGO), corporate and citizen cooperation. Survey coordination is contracted through Limuli Labs and the University of Delaware. Data entry is completed by staff from the New Jersey Department of Environmental Protection and USGS and DE DFW staff oversee data analysis and report preparation. The vast sampling effort is conducted by a large contingent of dedicated private citizens, state and federal agencies, corporations, and NGO's.

This report is a continuation of a series of statistical reports on the survey and is meant to compliment the ongoing series of reports issued by the survey coordinators, Ms. Benjie Swan and Dr. William Hall in cooperation with Dr. Carl N. Shuster Jr.

Survey Objectives

The Delaware Bay Horseshoe Crab Spawning Survey has several important objectives:

1) provide a reliable index of spawning activity to monitor the temporal and spatial distribution of horseshoe crab spawning activity for comparing baywide spawning among years, beach-level spawning within Delaware Bay, and distributions of spawning horseshoe crabs and shorebirds;

2) increase our understanding of the relationship between environmental factors (tidal height, wave height, and water temperature) and spawning activity; and

3) promote public awareness of the central role of horseshoe crabs in shorebird population dynamics, Atlantic coast fisheries, and human health through the production of *Limulus* amebocyte lysate (LAL).

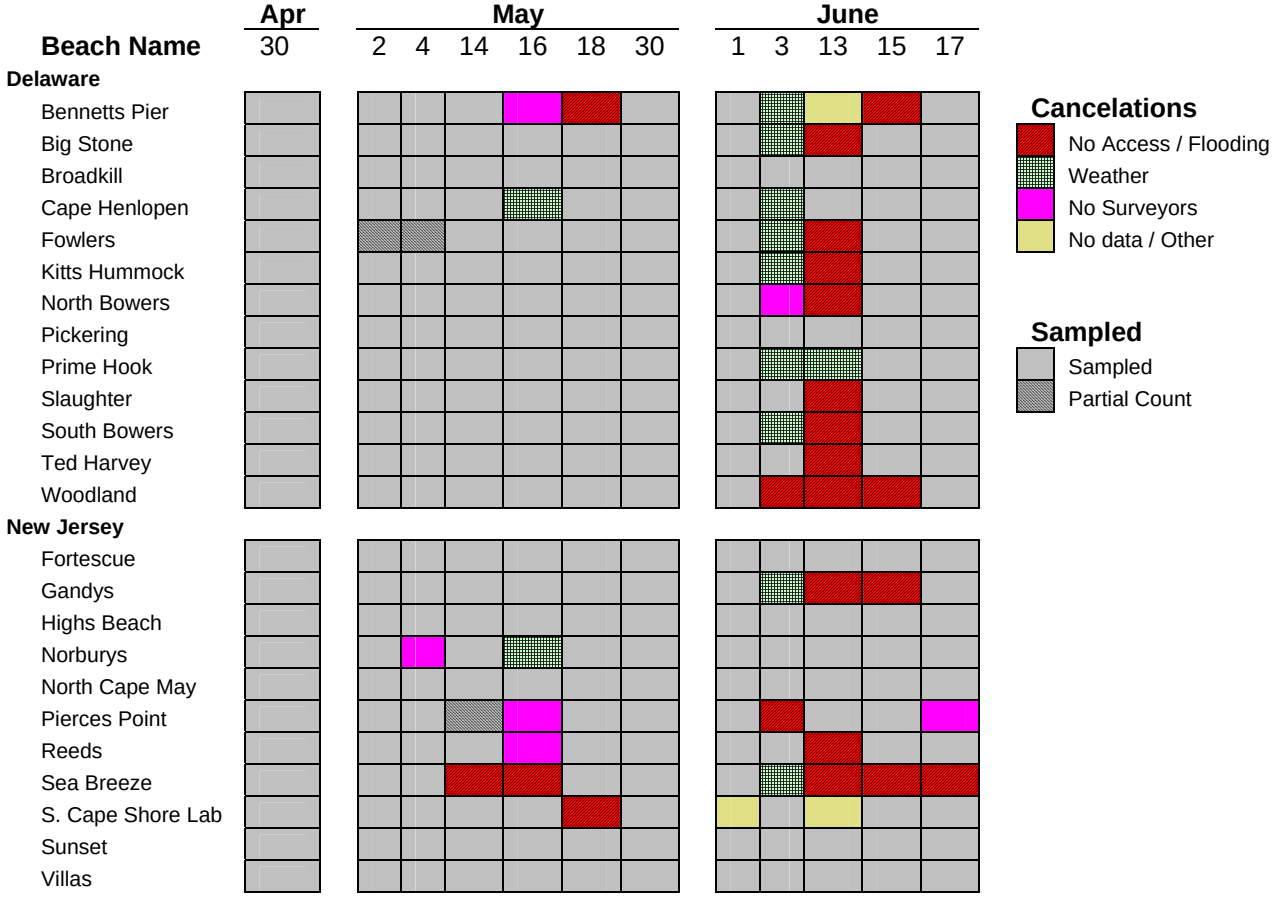
Data Availability

The spawning survey database was converted to MS ACCESS in 2004. A visual basic program was also developed by USGS to calculate estimates of spawning activity in tabular and graphic form. The conversion process revealed a number of errors that were corrected and detailed in Smith and Bennett (2005). The overall patterns of spawning activity were largely unaffected by these corrections. Data used in this report (both estimates and raw data) and the software used to calculate estimates are available on the internet at http://www.lsc.usgs.gov/aeb/2065/SPAWNAR/index.asp.

Summary Results

Sampling in 2007 was conducted during twelve nighttime high tides from 3 April through 17 June. Twenty-four (24) beaches were sampled in the Delaware Estuary – 13 in Delaware and 11 in New Jersey. The total number of tides sampled over the season was 245, with 43 sampling events canceled (Table 1).

Table 1. Beaches sampled in the 2007 Delaware Bay Horseshoe Crab Spawning Survey.



Temporal Spawning Distribution

Time of spawning is an important factor to examine as it gives an indication of potential food availability to migratory shorebirds. The time of spawning could also affect the survival of egg, larvae and juvenile stages.

Spawning during the first lunar period in 2007 was low, similar to 2003 and 2005 (Figure 1). Spawning during the second lunar phase was relatively high and peaked in the third lunar phase. In 2007, 42% of Delaware spawning activity and 45% of the New Jersey spawning activity occurred in May (Table 2). The percentage of spawning that occurred in May has been consistently higher in NJ than DE (Table 2; Figure 2).

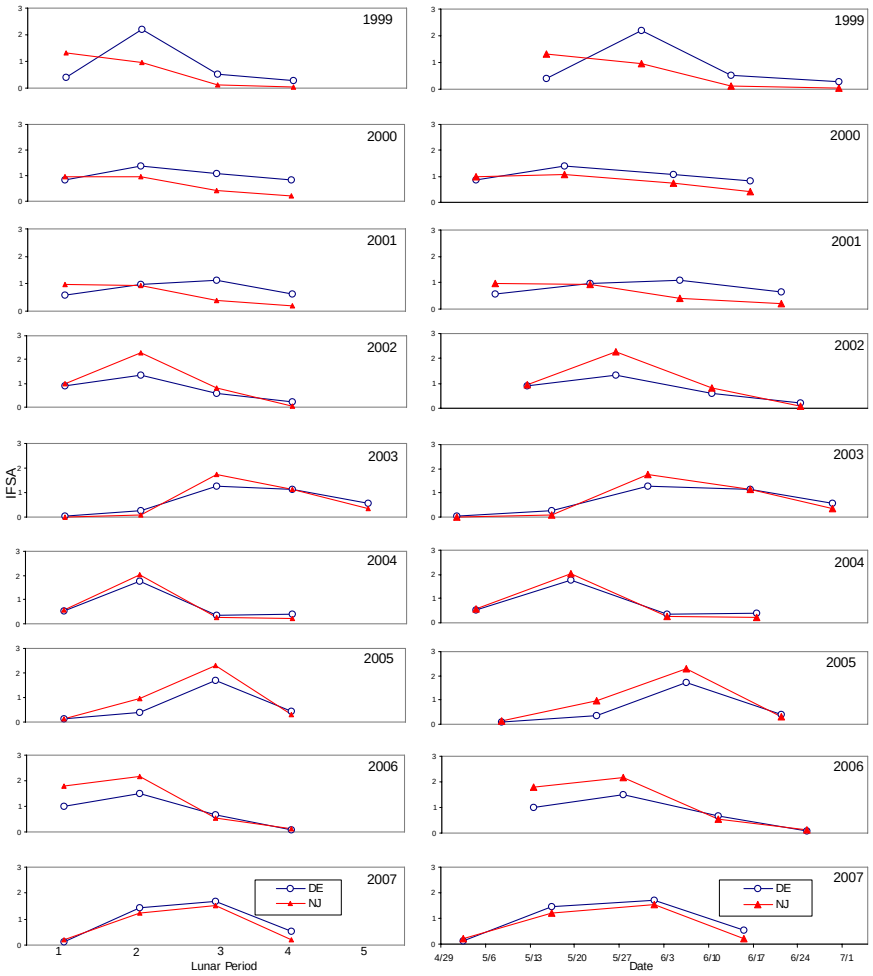


Figure 1. Temporal distribution of female horseshoe crab spawning activity in the Delaware Bay by state. Lunar periods are defined as a 5 day period (sampled day of lunar event and 2 days before and 2 days after) around the new or full moons in May and June.

Water temperature may influence the time of spawning (Smith and Michels 2006). Water temperature readings taken at Lewes, DE (Appendix I) suggest spawning was delayed in 2003 and 2005 when water temperatures

were not consistently above 15 °C until late May or early June. Water temperatures in 2007 remained consistently above 15 °C after 16 May. This date coincided with the second lunar sampling phase. There was a strong association between average May water temperatures recorded at Lewes, DE and the percentage state-specific spawning activity in May (r_{DE} = 0.75, P_{DE} = 0.02; r_{NJ} = 0.76, P_{NJ} = 0.02; Figure 2).

Table 2. Summary statistics reflecting the timing of female horseshoe crab spawning in Delaware and New Jersey and average May water temperatures. Percentages are based on estimates of month-specific index of female spawning activity (ISA). Water temperatures were recorded at the National Ocean Service station at Lewes, DE.

	Delaware		New Jersey		
Year	Dates of Peak Female Spawning	% of Female Spawning in May	Dates of Peak Female Spawning	% of Female Spawning in May	Average daily water temp. in May (C)
1999	28 May - 1 June	77	28 May - 1 June	93	16.2
2000	16 May - 18 May	54	16 May - 18 May	64	15.6
2001	3 June - 7 June	47	5 May - 9 May	76	16.0
2002	24 May - 28 May	73	24 May - 28 May	78	16.7
2003	29 May - 2 June	47	29 May - 2 June	56	13.4
2004	17 May - 21 May	76	17 May - 21 May	85	15.7
2005	4 June - 8 June	18	4 June - 8 June	30	13.7
2006	25 May - 29 May	77	25 May - 29 May	85	16.3
2007	30 May - 3 June	42	30 May - 3 June	45	15.4

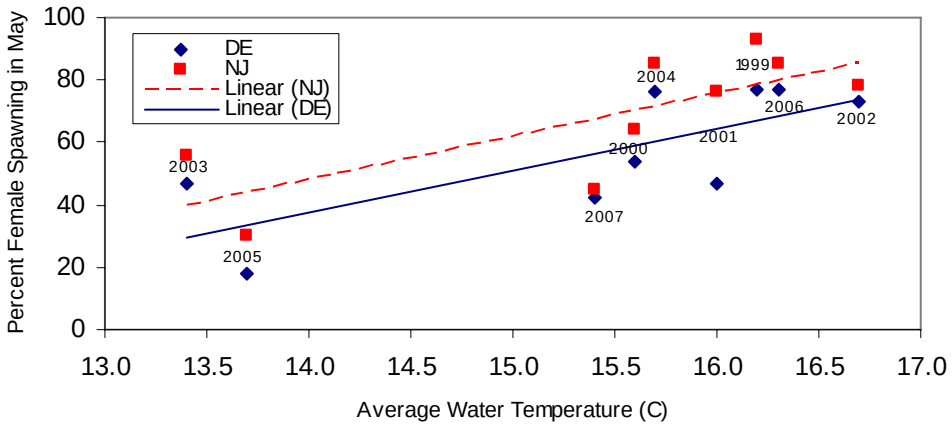


Figure 2. Percent of female horseshoe crab spawning occurring in May by state versus May average daily water temperatures. Water temperatures were recorded at the National Ocean Service at Lewes, DE Station ID 8557380.

State-specific Spawning Activity

Trends in female spawning activity differed by state (Figures 3; Table 3). Female spawning activity in New Jersey trended upward from 1999 through 2007, though not significantly (Slope = 0.04, SE = 0.02, P = 0.13). Spawning activity in Delaware exhibited a slightly negative slope, though not significant (Slope = -0.01, SE = 0.02, P = 0.35).

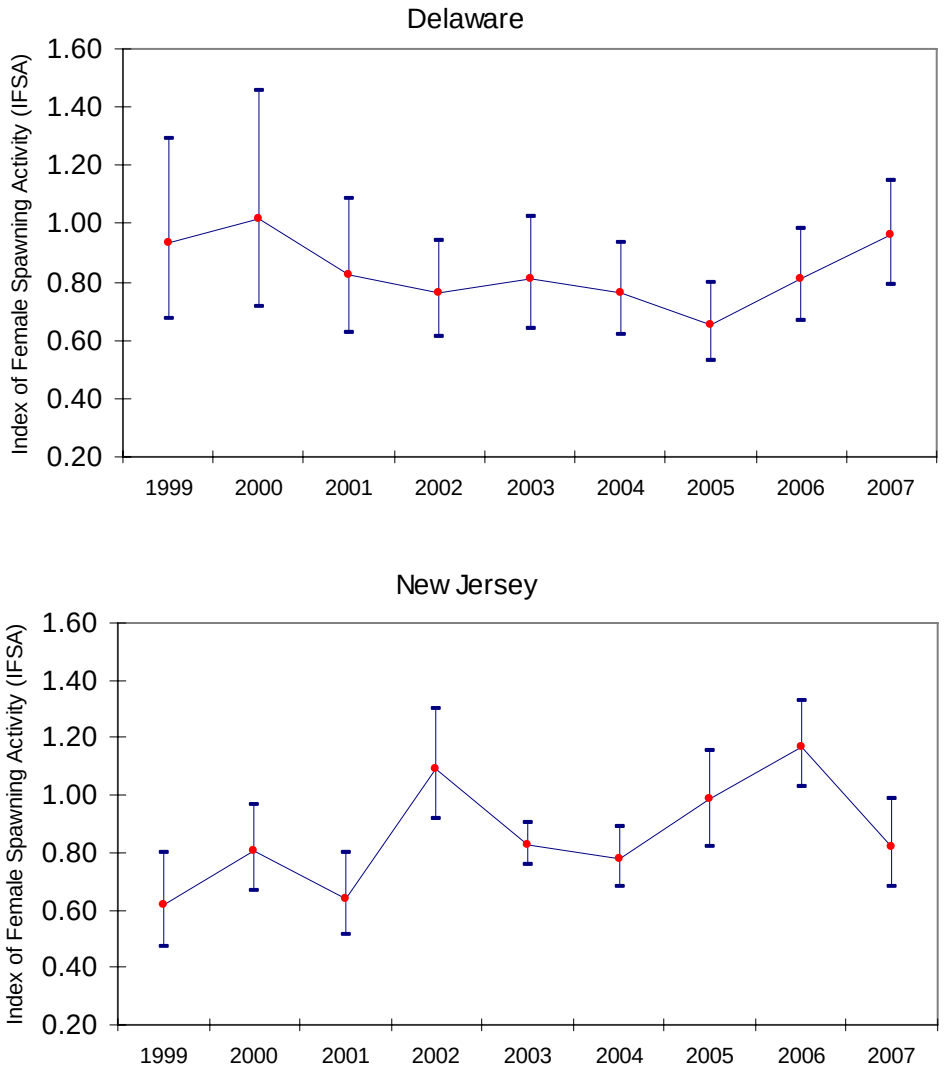


Figure 3. Indices of female horseshoe crab spawning activity (IFSA), expressed as the mean number of female crabs per m^2 per night, for the states of Delaware and New Jersey. Error bars are 90% confidence intervals.

Table 3. Indices of female horseshoe crab spawning activity (IFSA), expressed as the mean number of female crabs per m^2 per night, by state from 1999 to 2007.

	Delaware			New Jersey		
Year	IFSA	90% CI	Beaches Surveyed	IFSA	90% CI	Beaches Surveyed
1999	0.93	0.67, 1.29	8	0.61	0.47, 0.80	9
2000	1.02	0.72, 1.45	11	0.80	0.67, 0.96	11
2001	0.82	0.63, 1.08	12	0.64	0.51, 0.80	10
2002	0.76	0.61, 0.94	13	1.09	0.92, 1.30	10
2003	0.81	0.64, 1.03	13	0.83	0.76, 0.91	10
2004	0.76	0.62, 0.93	13	0.78	0.68, 0.89	12
2005	0.65	0.53, 0.80	13	0.99	0.84, 1.16	12
2006	0.81	0.67, 0.98	13	1.17	1.03, 1.33	11
2007	0.96	0.79,1.15	13	0.82	0.68, 0.99	11

Baywide Spawning Activity - Females

Trends in state-specific female spawning were compensatory, as no change in baywide spawning activity was detected (Figure 4; Table 4). The regression slope continues to be close to zero (Slope = 0.01, SE = 0.013, 90% CI = -0.01 to 0.04, P = 0.44). Coefficients of variation were below 14% over the entire survey period and below 10% since 2002.

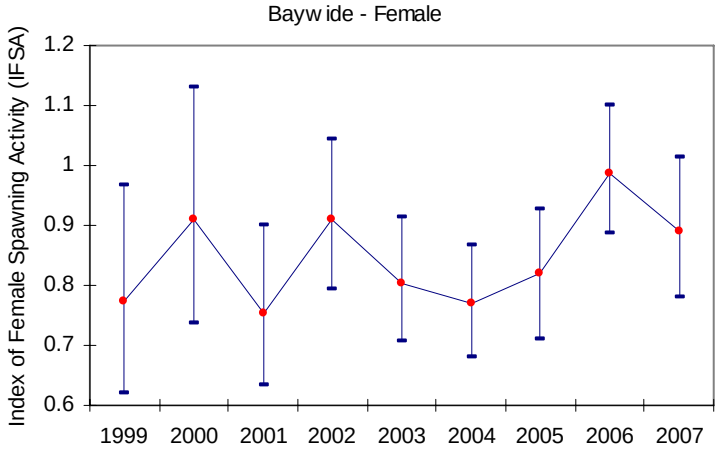


Figure 4. Index of female horseshoe crab spawning activity (IFSA) for the Delaware Bay from 1999 to 2007. Error bars are 90% confidence intervals.

Table 4. Index of female horseshoe crab (IFSA), standard error (SE), coefficient of variation (CV), and 90% confidence intervals (CI) for the Delaware Bay from 1999 to 2007.

Year	IFSA	Beaches Surveyed	SE	CV(%)	90% CI
1999	0.77	17	0.10	13	0.62, 0.97
2000	0.91	22	0.12	13	0.74, 1.13
2001	0.75	22	0.08	10	0.63, 0.90
2002	0.91	23	0.07	8	0.79, 1.04
2003	0.80	23	0.06	8	0.71, 0.91
2004	0.77	24	0.06	7	0.68, 0.87
2005	0.82	23	0.07	9	0.72, 0.93
2006	0.99	24	0.07	7	0.89, 1.10
2007	0.89	24	0.07	8	0.78, 1.01

Baywide Spawning Activity - Males

Sex-specific harvest requirements contained in Addendum IV to the Interstate Fishery Management Plan for Horseshoe Crab (ASMFC 2006) for Delaware and New Jersey (specifically a male-only harvest) prompted an examination of male spawning abundance. Male spawning activity increased significantly (Slope = 0.20, SE = 0.04, 90% CI = 0.11 to 0.28, $P < 0.01$) from 1999 through 2007 (Figure 5; Table 5). Coefficients of variation for the male component of the survey were below 20% for the entire sampling and less than 10% since 2002.

There is evidence to suggest that males typically recruit to the spawning population one or two molts prior to females (Carmichael, et al. 2003, Smith et al. in review); this may explain why significant increases in the female component of the survey have yet to be noted.

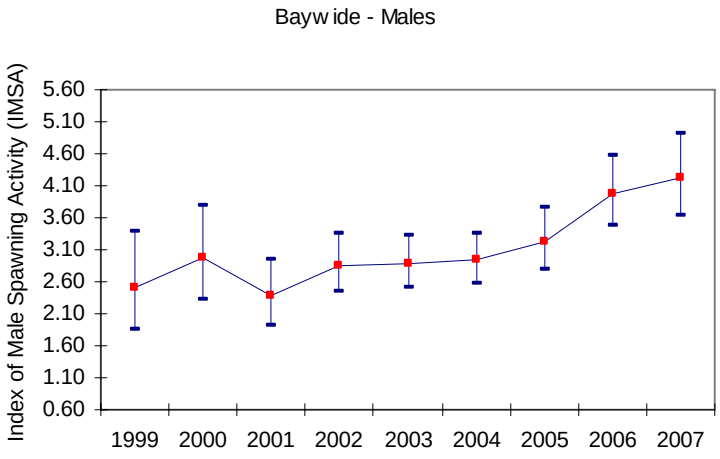


Figure 5. Index of male horseshoe crab spawning activity (IMSA) for the Delaware Bay from 1999 to 2007. Error bars are 90% confidence intervals.

Table 5. Index of male horseshoe crab (IMSA), standard error (SE), coefficient of variation (CV), and 90% confidence intervals (CI) for the Delaware Bay from 1999 to 2007.

Year	IMSA	Beaches Surveyed	SE	CV(%)	90% CI
1999	2.50	17	0.45	18	1.86, 3.37
2000	2.96	22	0.45	15	2.31, 3.80
2001	2.37	22	0.31	13	1.91, 2.95
2002	2.86	23	0.27	9	2.45, 3.34
2003	2.89	23	0.25	9	2.50, 3.33
2004	2.93	24	0.24	8	2.55, 3.36
2005	3.23	23	0.29	9	2.79, 3.74
2006	3.99	24	0.33	8	3.49, 4.56
2007	4.22	24	0.38	9	3.63, 4.90

Recommendations from Shorebird Technical Committee

The Shorebird Technical Committee (SBTC) requested a summary of baywide spawning activity by half month periods, which is important for understanding the synchronization of bird migration with horseshoe crab spawning. Lunar periods are essentially half-month periods. This information is provided in Figure 6 and Table 6.

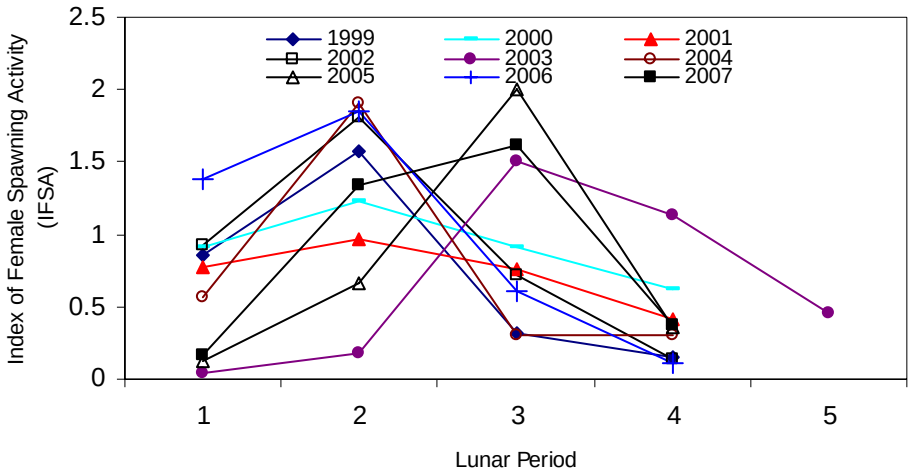


Figure 6. Baywide horseshoe crab spawning activity, expressed as mean number of spawning female crabs per m^2 per night, by lunar period for the years 1999 to 2007.

Table 6. Baywide horseshoe crab spawning activity, expressed as mean number of spawning female crabs per m^2 per night, by lunar period for the years 1999 to 2007.

	Lunar Period				
Year	1	2	3	4	5
1999	0.86	1.58	0.32	0.15	
2000	0.92	1.23	0.91	0.62	
2001	0.77	0.96	0.76	0.42	
2002	0.92	1.81	0.71	0.14	
2003	0.04	0.17	1.51	1.13	0.46
2004	0.56	1.91	0.30	0.30	
2005	0.12	0.67	2.00	0.36	
2006	1.39	1.85	0.61	0.11	
2007	0.17	1.34	1.61	0.38	

Though the SBTC requested, “an analysis of just the beaches consistently sampled for all years of the study”, this would be contrary to the survey’s design. Appendix II, however, provides a summary of spawning activity by beach for all years.

Literature Cited

Atlantic States Marine Fisheries Commission (ASMFC). 1998. Interstate fishery management plan for horseshoe crab. Fishery Management Report No. 32, Atlantic States Marine Fisheries Commission, Washington D.C.

Atlantic States Marine Fisheries Commission (ASMFC). 2006. Addendum IV to the Interstate Fishery Management Plan for Horseshoe Crab. Fishery Management Report No. 32d, Atlantic States Marine Fisheries Commission, Washington D.C.

Carmichael, R.H., D. Rutecki and I. Valiela. 2003. Abundance and population structure of the Atlantic horseshoe crab Limulus polyphemus in Pleasant Bay, Cape Cod. *Marine Ecol. Prog. Ser.* 246:225-239.

Finn, J.J., C.N. Shuster, Jr. and B.L. Swan. 1991. *Limulus* spawning activity on Delaware Bay shores 1990. Finn-Tech Inc., Cape May Courthouse, NJ.

Maio, K.J. 1998. Quantitative description of the temporal and spatial patterns in spawning activity of the horseshoe crab, *Limulus polyphemus*. Master's thesis. University of Maryland Eastern Shore, Princess Anne, Maryland.

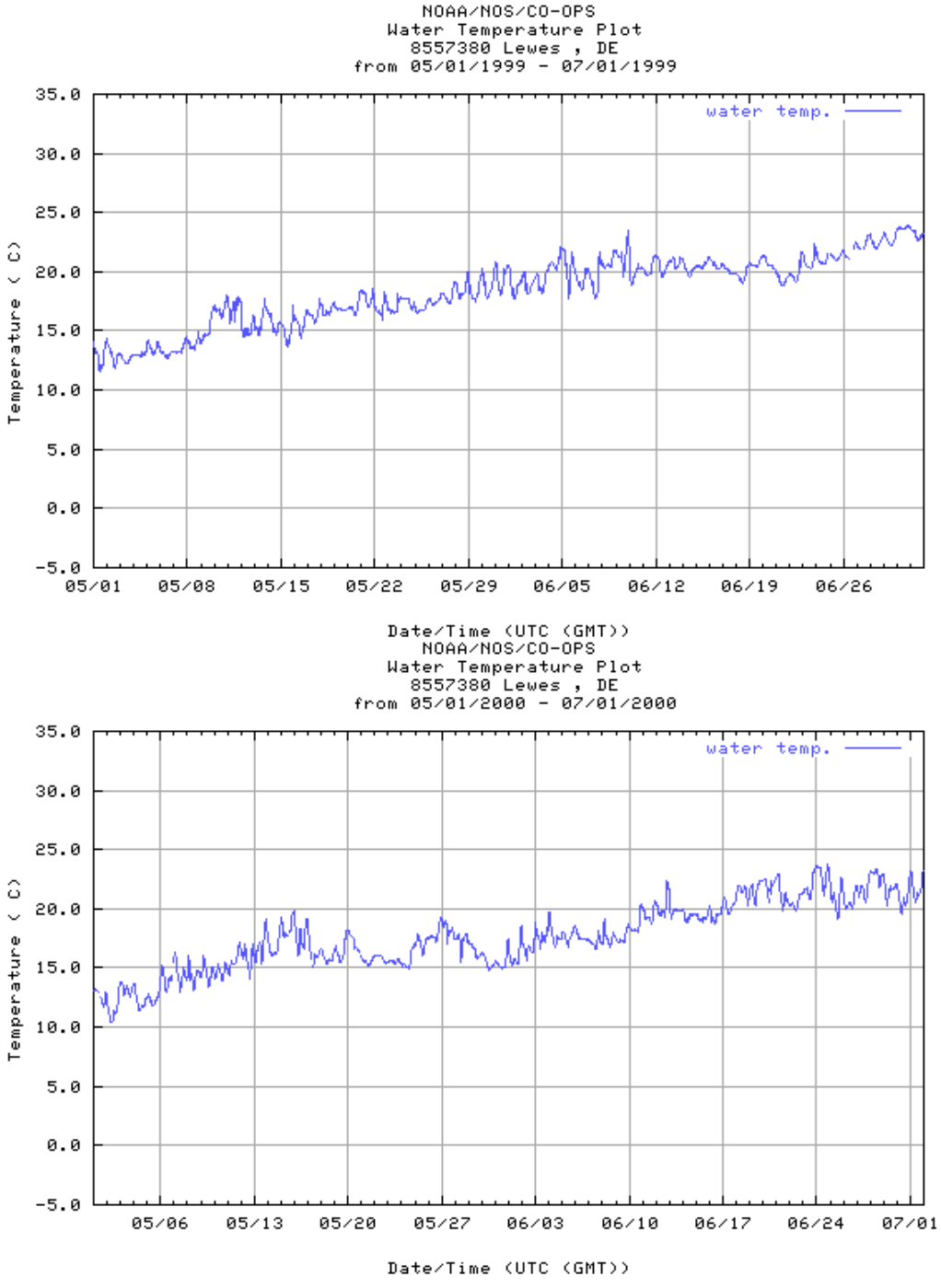
Smith, D.R., P.S. Pooler, B.L. Swan, S.F. Michels, W.R. Hall, P.J. Himchak, and M.J. Millard. 2002. Spatial and temporal distribution of horseshoe crab (*Limulus polyphemus*) spawning in Delaware Bay: implications for monitoring. Estuaries 25(1):115-125.

Smith D.R. and S. Bennett. 2005. Horseshoe crab spawning activity in Delaware Bay: 1999 – 2004. Report to the ASMFC Horseshoe Crab Management Board. Unpublished.

Smith, D.R., and S.F. Michels. 2006. Seeing the elephant: importance of spatial and temporal coverage in a large-scale volunteer-based program to monitor horseshoe crabs. Fisheries 31(10):485-491.

Smith, D. R., M. T. Mandt, and P. D. M. Macdonald. (in review) Sexual size dimorphism in Delaware Bay horseshoe crabs (*Limulus polyphemus*): a test of competing hypotheses. Biological Bulletin

APPENDIX I. May 1 – July 1 water temperature data from Lewes, DE (Station identification Number 8557380; Latitude 38° 46.9' N / Longitude 75° 7.2' W) for the years 1999 through 2007. Source: Center for Operational Oceanographic Products and Services (CO-OPS).



NOAA/NOS/CO-OPS
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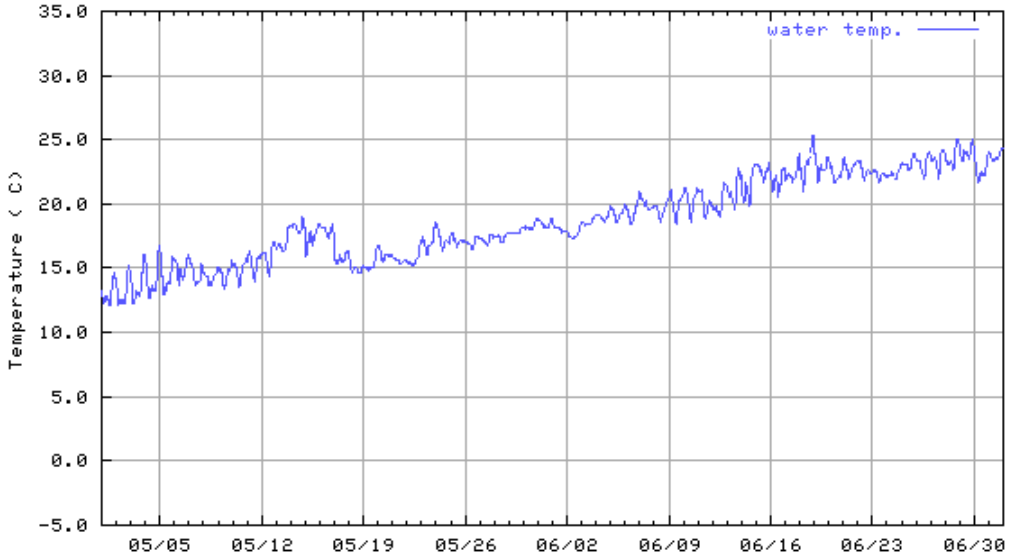

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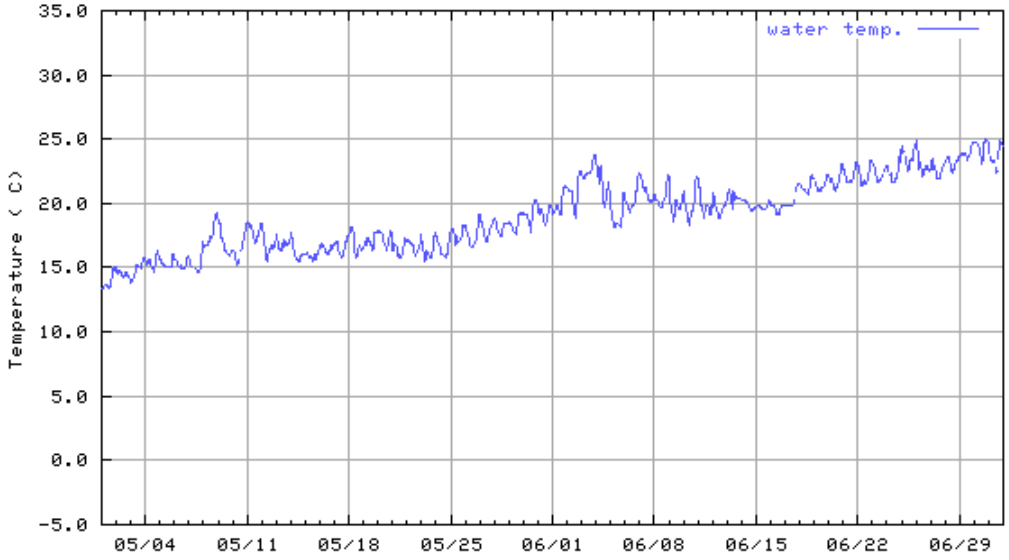

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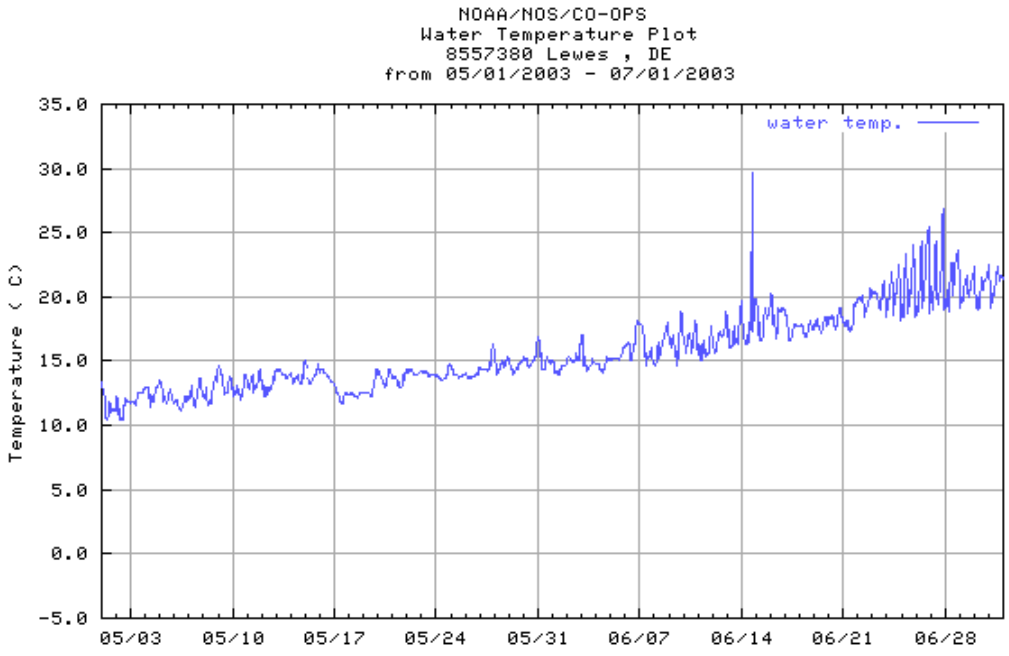
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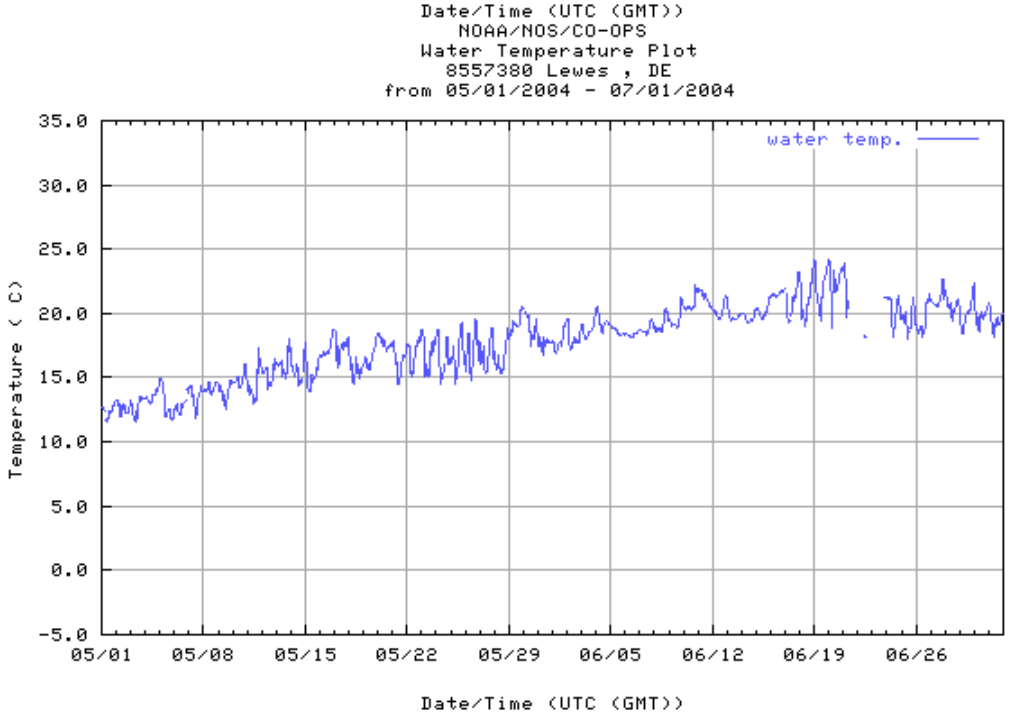
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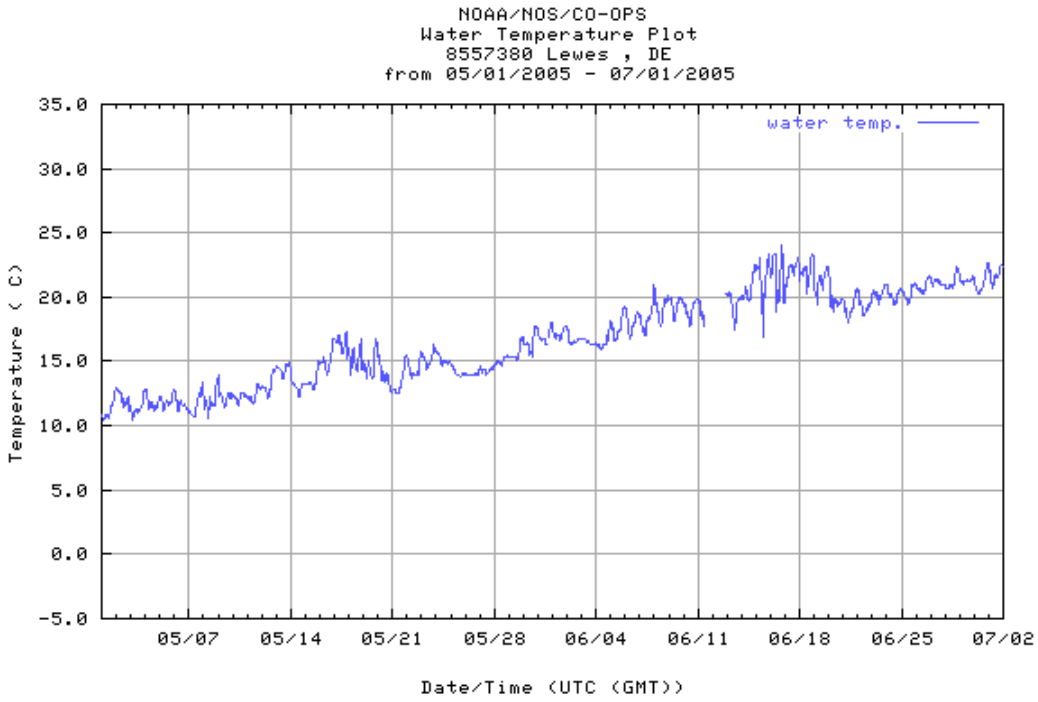
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water temp.
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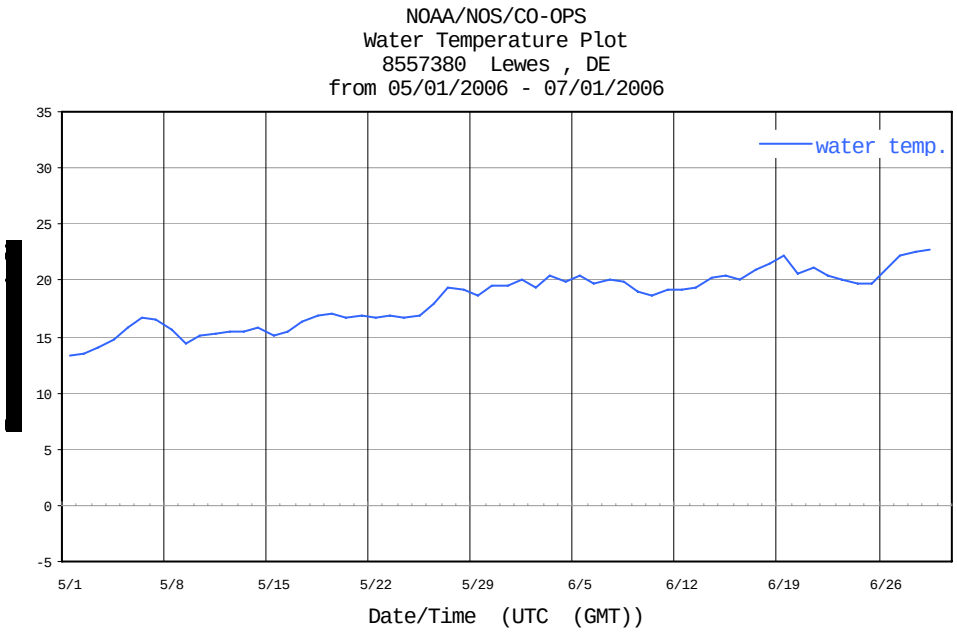
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Water Temperature Plot
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Water Temperature Plot
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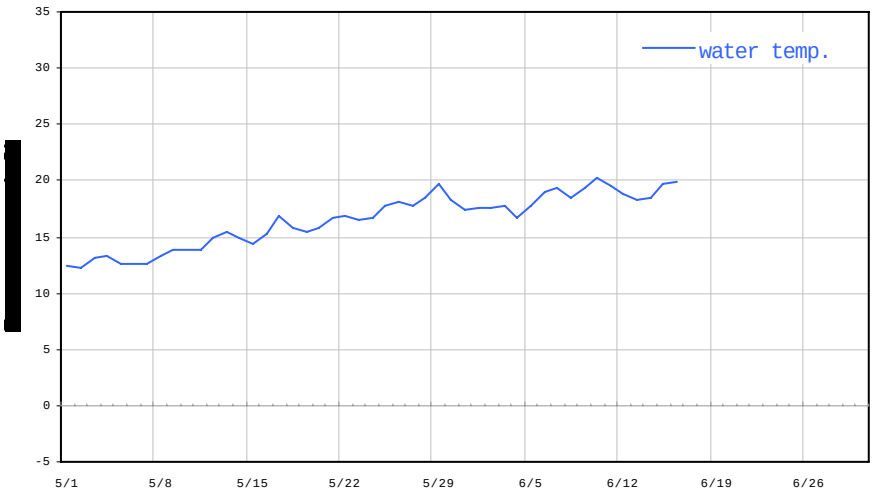
from 05/01/2007 - 07/01/2007



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APPENDIX II. Index of female spawning horseshoe crabs abundance, expressed as the mean number of females crabs per m^2 per night, for Delaware Bay beaches surveyed from 1999 to 2007.

	State Beach	1999	2000	2001	2002	2003	2004	2005	2006	2007
DE	Bennetts Pier		0.2233	0.6399	0.4713	0.2762	0.5470	0.6992	0.6117	0.5496
DE	Big Stone	0.7462	0.7290	0.8562	0.6265	0.6370	0.7617	0.8088	1.0896	1.3475
DE	Broadkill	0.3197	0.0638	0.1170	0.1347	0.2083	0.1741	0.1911	0.1208	0.1775
DE	Cape Henlopen				0.0857	0.1816	0.1255	0.2694	0.1000	0.0579
DE	Fowlers	0.7779	0.4933	0.7033	0.2370	0.4532	0.6110	0.2148	0.4077	0.5033
DE	Kitts Hummock	2.1510	2.5830	2.3545	1.4667	1.5529	1.2394	1.4175	1.7237	1.4394
DE	Lewes				0.0838					
DE	North Bowers	0.8806	1.1836	1.0383	1.2142	0.9802	0.4995	0.6012	0.7479	1.1088
DE	Pickering		3.3047	1.6244	1.6950	1.6417	1.6380	1.4708	1.4933	1.6350
DE	Prime Hook	0.5984	0.1872	0.4446	0.5908	0.4733	0.7596	0.6500	0.7283	1.1088
DE	Slaughter	1.6190	1.3254	1.0962	0.7265	1.6508	1.5237	0.6805	1.0396	1.2360
DE	South Bowers		0.9196	0.8433	1.1265	0.4685	0.4796	0.6343	0.7192	1.3026
DE	Ted Harvey				1.4446	1.9852	1.5220	0.8162	1.4579	1.9279
DE	Woodland	0.1368	0.1033	0.0292	0.0792	0.0075	0.0012	0.0062	0.2700	0.0312
NJ	East Point		0.3458							
NJ	Fortescue	0.2473				0.4184	0.5408	0.5818	0.6525	0.1600
NJ	Gandys	0.4014	0.3922	0.4521	1.4122	0.5498	0.8166	0.8788	1.1652	0.8257
NJ	Higbees		0.0361					0.1368		
NJ	Highs Beach	0.7892	0.9594	0.7950	0.4685	0.5275	0.6963	0.7583	0.6933	0.7527
NJ	Kimbles	0.7063	0.8521	0.4773	0.4976	0.4970	0.4054			
NJ	Norburys			0.4600	0.6242	0.5362	0.6707	0.9391	0.6936	0.4334
NJ	North Cape May	0.2250	0.0500	0.0904	0.0845	0.1233	0.0200	0.1233	0.0229	0.0417
NJ	Pierces Point		0.6138		0.6730	0.7300	0.9602	0.8275	0.7447	0.9410
NJ	Raybins	0.0259								
NJ	Reeds	0.3808	0.6468	0.4049	0.8768	0.8225	0.4162	0.2398	0.9650	0.3050
NJ	Sea Breeze	0.0947	0.1094	0.2991	1.6283	0.3892	0.4275	0.2088	0.8471	0.9250
NJ	Cape Shore Lab	1.2452	1.3311	1.2775	0.6850	0.6283	0.9042	1.1684	0.8183	1.2610
NJ	Sunset			0.1139					0.0119	0.0038
NJ	Townbank			0.7362	0.3958	0.4589	0.2037			0.2883
NJ	Villas							0.7075	0.4833	