Horseshoe Crab Spawning Activity in Delaware Bay: 1999 – 2009

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

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March 26, 2010

Summary

- This marks the eleventh 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 eight years.
- Female spawning activity in 2009 peaked during the second lunar period sampled (May 22 - 26).
- Most female spawning activity in 2009 was observed in May (59% in DE and 66% in NJ).
- Percent of female spawning that occurred in May was associated with water temperature (correlations were 0.74 and 0.66 for DE and NJ, respectively).
- Baywide female spawning activity over the past 11 years remained stable (Slope = 0.01, SE = 0.01, 90% CI = -0.01 to 0.03, P = 0.52).
- 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.
- Estimates of male spawning activity were precise. Annual coefficients of variation were below 20% for the entire series.
- Baywide male spawning activity showed a significantly positive trend from 1999 through 2009 (Slope = 0.15, SE = 0.06, 90% CI = 0.04 to 0.26, P = 0.04).
- Sex ratios (M:F) ranged from 3.1 to 4.7 and have increasingly favored males in recent years.

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

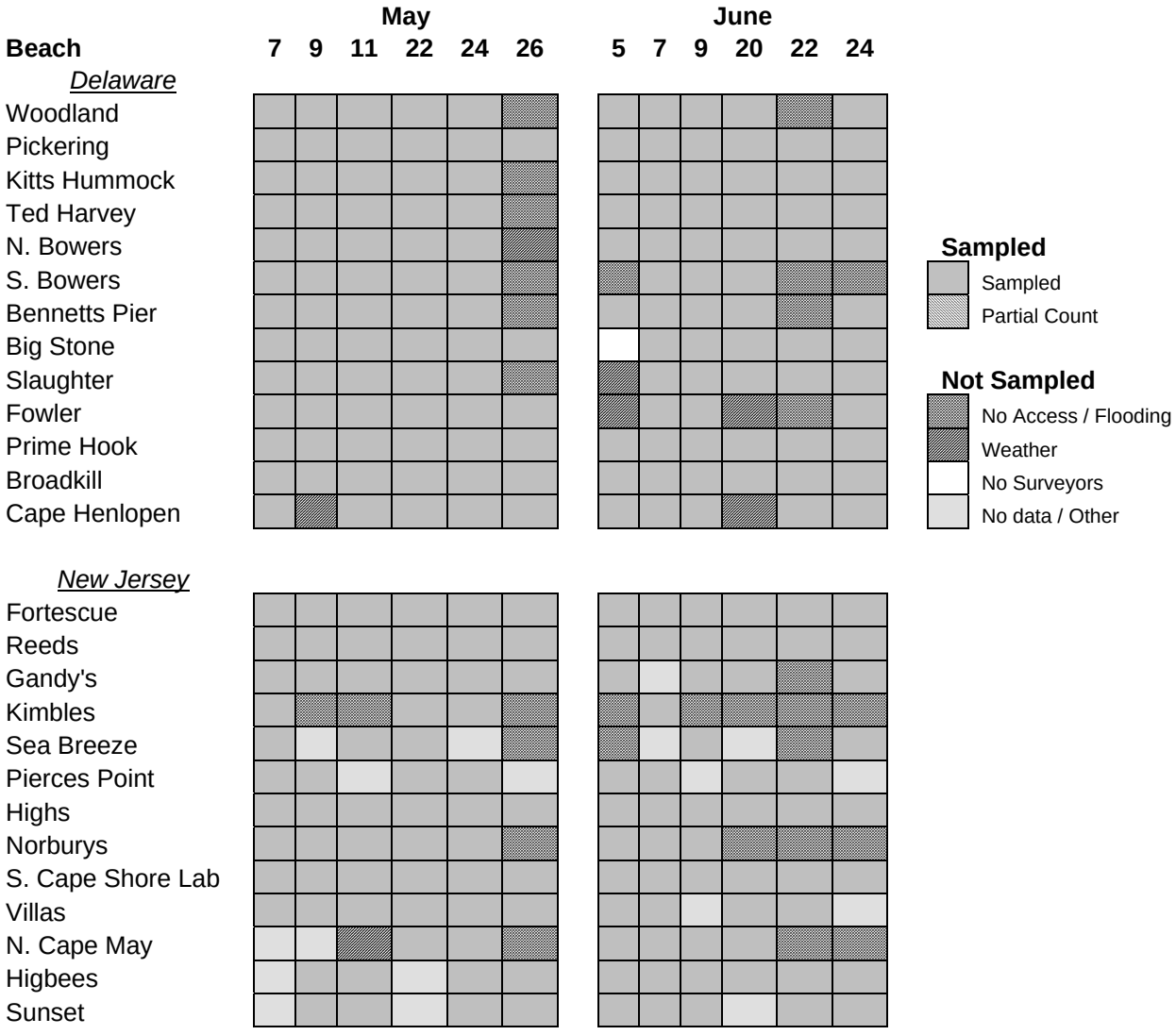
The spawning survey database was converted to MS ACCESS in 2004. A visual basic program was also developed by USGS to calculate estimates of spawning activity in tabular and graphic form. The conversion process revealed a number of errors that were corrected and detailed in Smith and Bennett (2005). 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 by request.

Summary Results

Sampling in 2009 was conducted during twelve nighttime high tides from 7 May through 24 June. Twenty-six (26) beaches were sampled in the Delaware Estuary – 13 in Delaware and 13 in New Jersey. The total number of tides sampled over the season was 255, with 57 sampling events canceled (Table 1).

Table 1. Beaches sampled in the 2009 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 may also affect the survival of egg, larvae and juvenile stages.

State-specific spawning activity during the first lunar sampling period (May 7 – 11) in 2009 was moderate relative to previous sampling (Figure 1). Peak spawning activity was measured over the second lunar period (May 22-26). This pattern was similar to the years 2000, 2002 and 2004. Fifty-nine percent (59%) of the annual spawning activity in Delaware and 66% of the annual spawning activity in New Jersey was observed in May (Table 2). The proportion of annual state-specific spawning activity that occurred in May was higher in New Jersey in every year except 2008.

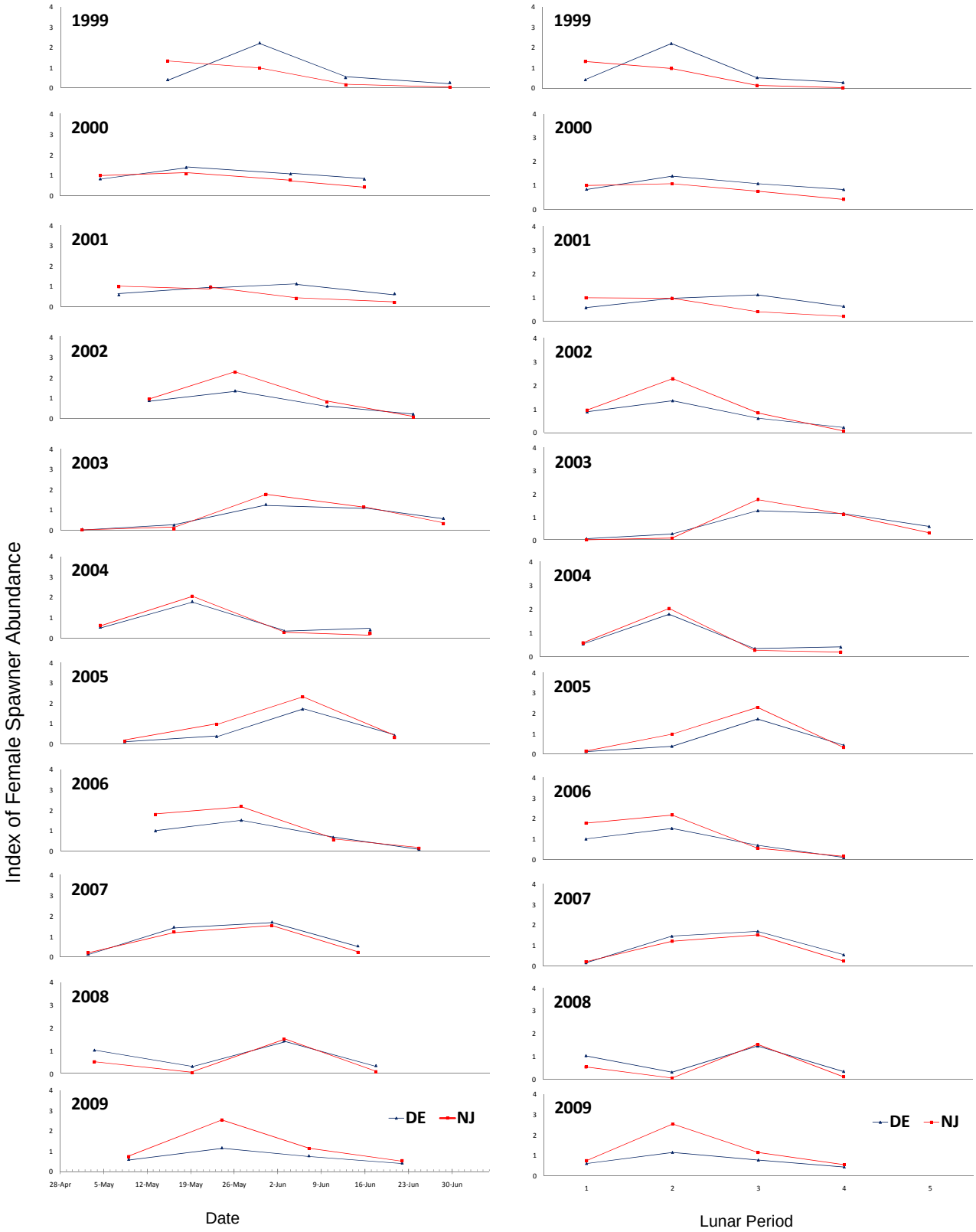


Figure 1. Temporal distribution of female horseshoe crab spawning activity in the Delaware Bay by state. Lunar periods are defined as a 5 day period (sampled day of lunar event and 2 days before and 2 days after) around the new or full moons in May and June.

Water temperature may influence the time of spawning (Smith and Michels 2006). There was a strong association between average May water temperatures recorded at Lewes, DE and the percentage state-specific female spawning activity in May (r_{DE} = 0.74, P_{DE} = 0.01; r_{NJ} = 0.66, P_{NJ} = 0.03; Figure 2). Daily average water temperatures recorded at Lewes, DE (Appendix I) suggested spawning was delayed in 2003 and 2005 when water temperatures were not consistently above 15 °C until late May or early June. Reduced spawning activity noted during the second lunar sampling period in 2008 coincided with a severe nor'easter that depressed water temperatures. Water temperatures in 2009 were above 15 °C by May 9 (coinciding with the first lunar sampling event) and remained consistently above 15 °C by May 16 (prior to the second lunar sampling event).

Table 2. Summary statistics reflecting the timing of female horseshoe crab spawning in Delaware and New Jersey and average May water temperatures. 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
2008	1 June - 5 June	43	1 June - 5 June	26	15.2
2009	22 May - 26 May	59	22 May - 26 May	66	15.5

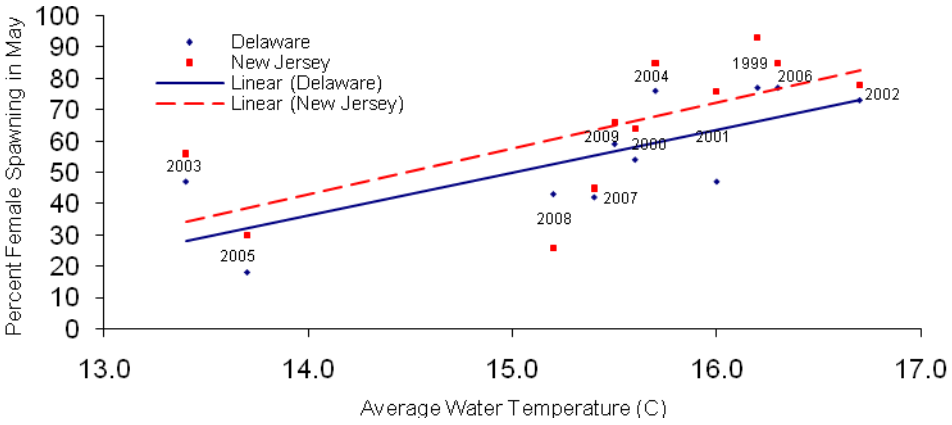


Figure 2. Percent of female horseshoe crab spawning occurring in May by state versus May average daily water temperatures. Water temperatures were recorded by the National Ocean Service at Lewes, DE Station ID 8557380.

State-specific Spawning Activity

Trends in female spawning activity differed by state (Figure 3; Table 3). The index of female spawning activity in Delaware exhibited a slightly negative slope, though not significant (Slope = -0.01, SE = 0.01, P = 0.16). Female spawning activity in New Jersey trended upward, though not significantly (Slope = 0.03, SE = 0.02, P = 0.21).

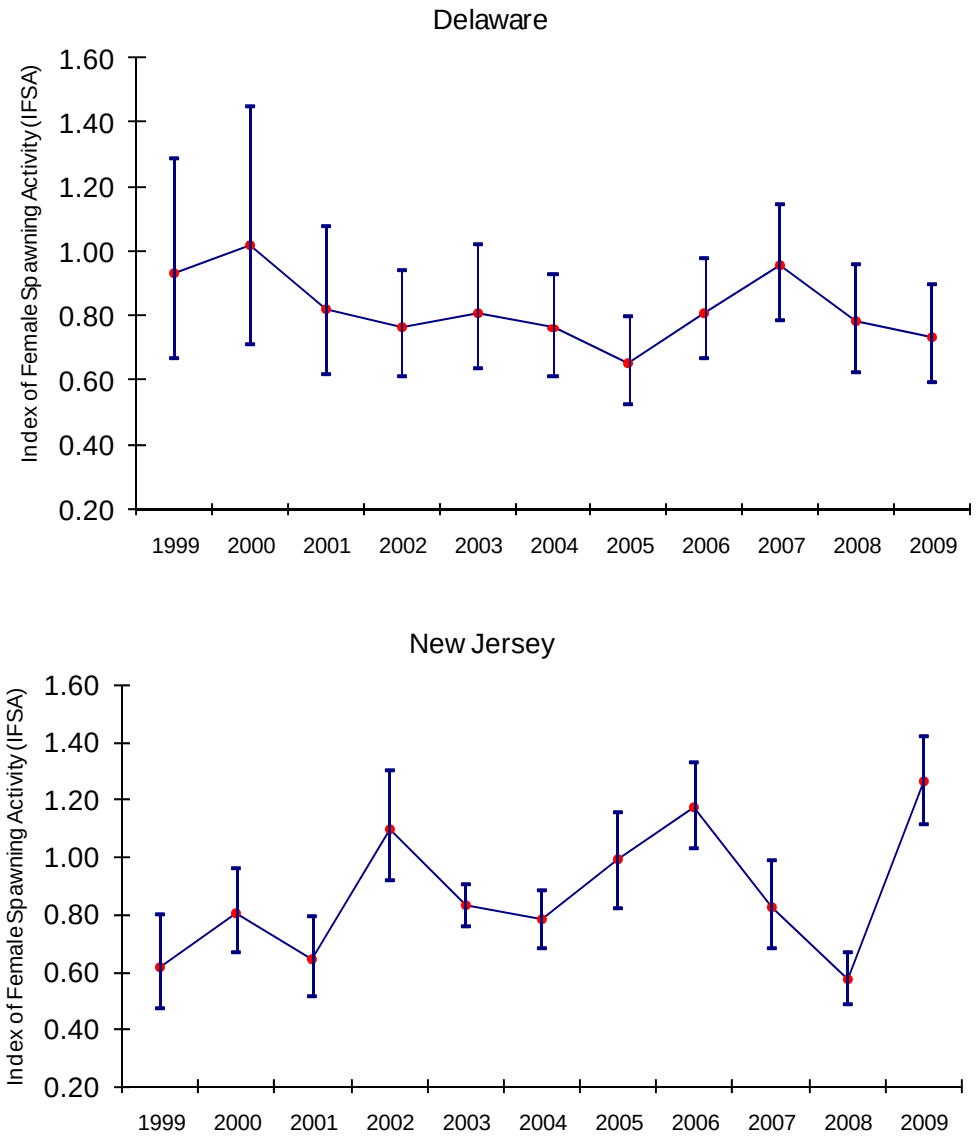


Figure 3. Indices of female horseshoe crab spawning activity (IFSA), expressed as the mean number of female crabs per m^2 per night, for the states of Delaware and New Jersey. Error bars are 90% confidence intervals.

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 2009.

	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
2008	0.78	0.63, 0.96	13	0.57	0.49, 0.67	12
2009	0.73	0.60, 0.90	13	1.26	1.11, 1.42	13

Baywide Spawning Activity - Females

Trends in state-specific female spawning activity were compensatory, as no change in baywide spawning activity was detected (Figure 4; Table 4). The regression slope was close to zero (Slope = 0.01, SE = 0.01, 90% CI = -0.01 to 0.03, P = 0.52). Coefficients of variation were below 14% over the entire survey period and below 10% since 2002.

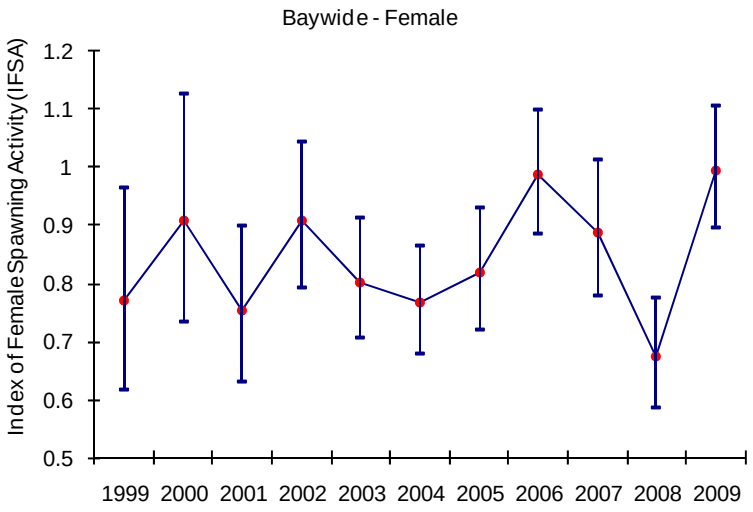


Figure 4. Index of female horseshoe crab spawning activity (IFSA) for the Delaware Bay from 1999 to 2009. Error bars are 90% confidence intervals.

Table 4. Indices of baywide male and female horseshoe crab spawning activity (ISA), number of beaches surveyed, standard errors (SE), coefficient of variations (CV), 90% confidence intervals (CI) and sex ratio for the Delaware Bay from 1999 to 2009.

		Male				Female				Annual
Year	Beaches Surveyed	**ISA**	90% CI	SE	CV (%)	**ISA**	90% CI	SE	CV (%)	Sex Ratio (M:F)
1999	17	**2.50**	1.86, 3.37	0.45	18	**0.77**	0.62, 0.97	0.10	13	3.2
2000	22	**2.96**	2.31, 3.80	0.45	15	**0.91**	0.74, 1.13	0.12	13	3.2
2001	22	**2.37**	1.91, 2.95	0.31	13	**0.75**	0.63, 0.90	0.08	10	3.1
2002	23	**2.86**	2.45, 3.34	0.27	9	**0.91**	0.79, 1.04	0.07	8	3.1
2003	23	**2.89**	2.50, 3.33	0.25	9	**0.80**	0.71, 0.91	0.06	8	3.6
2004	24	**2.93**	2.55, 3.36	0.24	8	**0.77**	0.68, 0.87	0.06	7	3.8
2005	23	**3.23**	2.79, 3.74	0.29	9	**0.82**	0.72, 0.93	0.07	9	3.9
2006	24	**3.99**	3.49, 4.56	0.33	8	**0.99**	0.89, 1.10	0.07	7	4.0
2007	24	**4.22**	3.63, 4.90	0.38	9	**0.89**	0.78, 1.01	0.07	8	4.7
2008	25	**2.30**	1.83, 2,90	0.32	14	**0.68**	0.59, 0.78	0.06	9	3.4
2009	26	**4.67**	4.11, 5.29	0.36	8	**1.00**	0.89, 1.11	0.06	6	4.7

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 significantly increased (Slope = 0.14, SE = 0.06, 90% CI = 0.04 to 0.26, P = 0.04) from 1999 to 2009 (Figure 5; Table 4). Coefficients of variation for the male component of the survey were below 20% for the entire sampling.

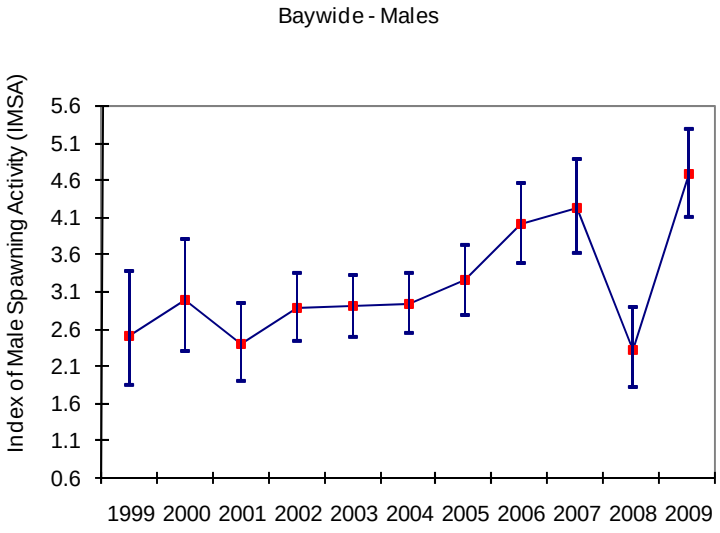


Figure 5. Index of male horseshoe crab spawning activity (IMSA) for the Delaware Bay from 1999 to 2009. Error bars are 90% confidence intervals.

Survey Sex Ratios

Current horseshoe crab harvest management strategies in the Delaware Bay area favor the harvest of male crabs. Concern was expressed that these strategies may skew spawning sex ratios (M:F) and negatively affect spawning and egg fertilization. Annual sex ratios have ranged from 3.1 to 4.7 over the course of the survey (Table 4). As suggested by the sex-specific trends in spawning activity, sex ratios have increasingly favored males in recent years.

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.

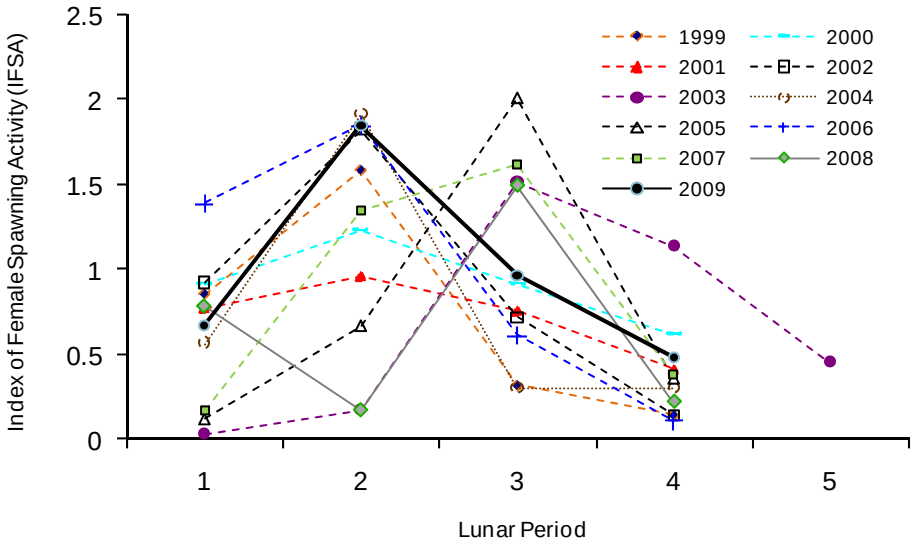


Figure 6. Baywide horseshoe crab spawning activity, expressed as mean number of spawning female crabs per m^2 per night, by lunar period for the years 1999 to 2009.

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 2009.

	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	
2008	0.78	0.17	1.49	0.22	
2009	0.67	1.84	0.96	0.48	

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.

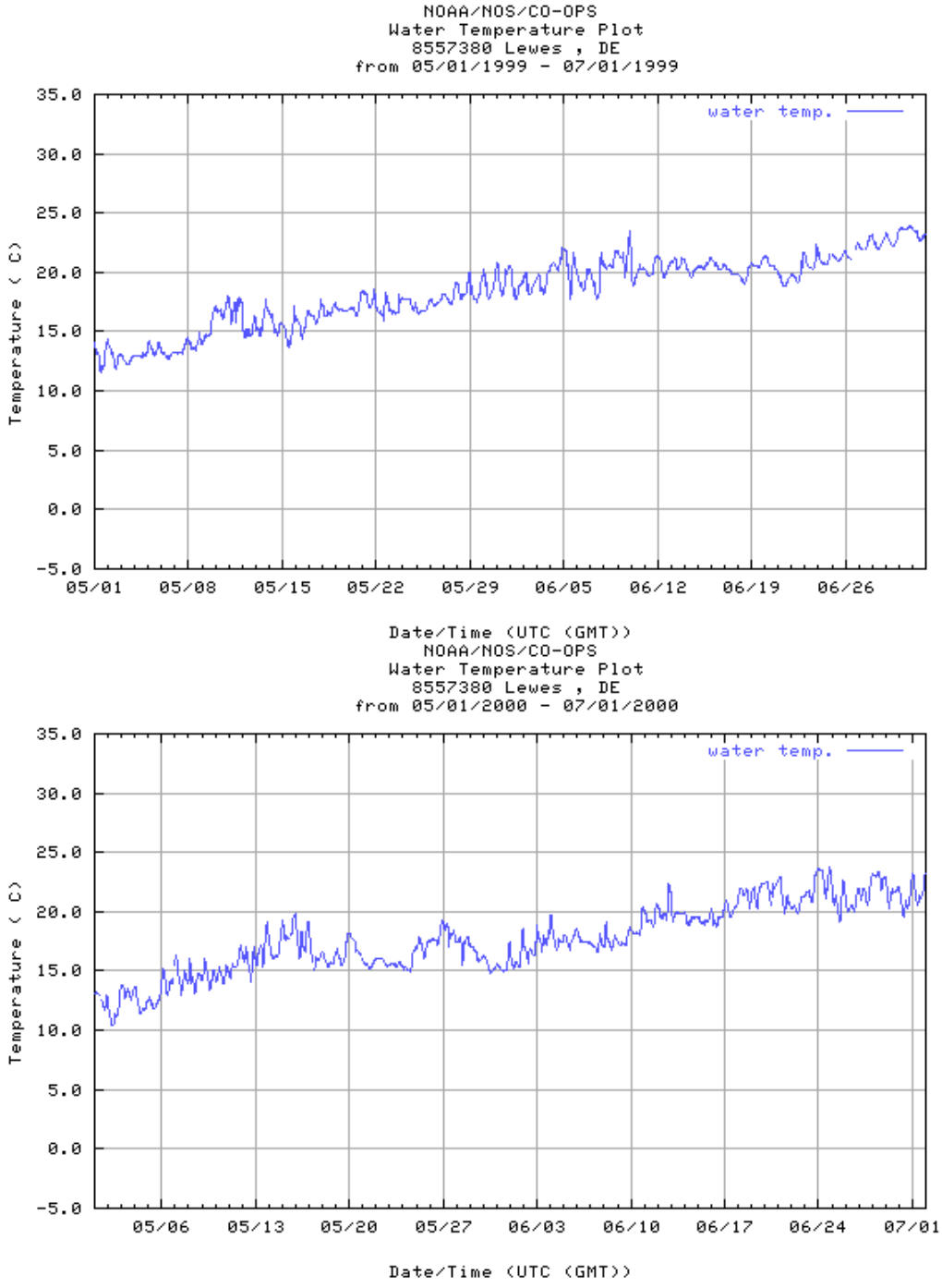
Maio, K.J. 1998. Quantitative description of the temporal and spatial patterns in spawning activity of the horseshoe crab, *Limulus polyphemus*. Master's thesis. University of Maryland Eastern Shore, Princess Anne, Maryland.

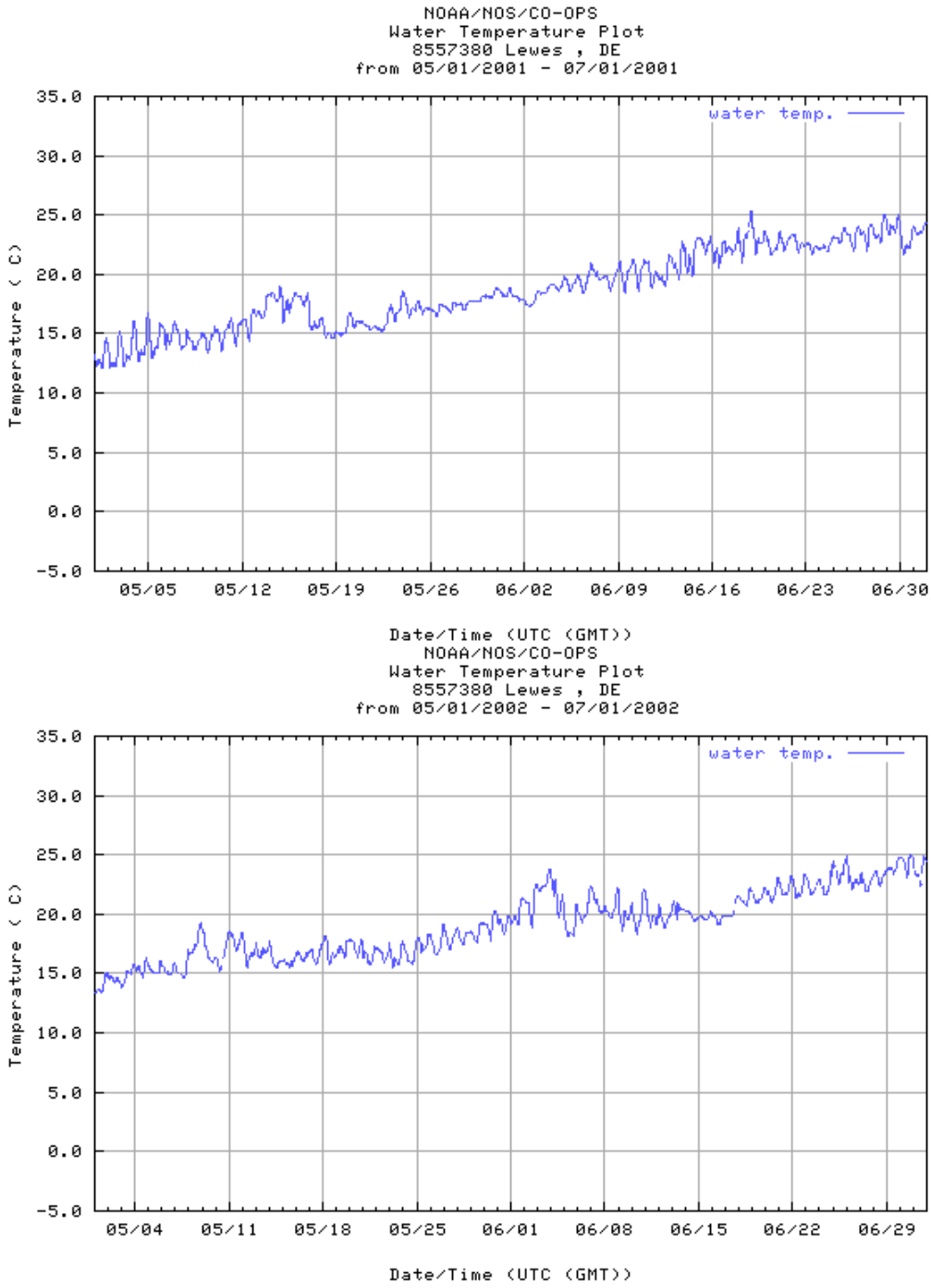
Smith, D.R., P.S. Pooler, B.L. Swan, S.F. Michels, W.R. Hall, P.J. Himchak, and M.J. Millard. 2002. Spatial and temporal distribution of horseshoe crab (*Limulus polyphemus*) spawning in Delaware Bay: implications for monitoring. Estuaries 25(1):115-125.

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.

APPENDIX I. 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 2009. Source: Center for Operational Oceanographic Products and Services (CO-OPS).

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Water Temperature Plot
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water temp.
Temperature (C)
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Date/Time (UTC (GMT))
NOAA/NOS/CO-OPS
Water Temperature Plot
8557380 Lewes , DE
from 05/01/2002 - 07/01/2002
water temp.
Temperature (C)
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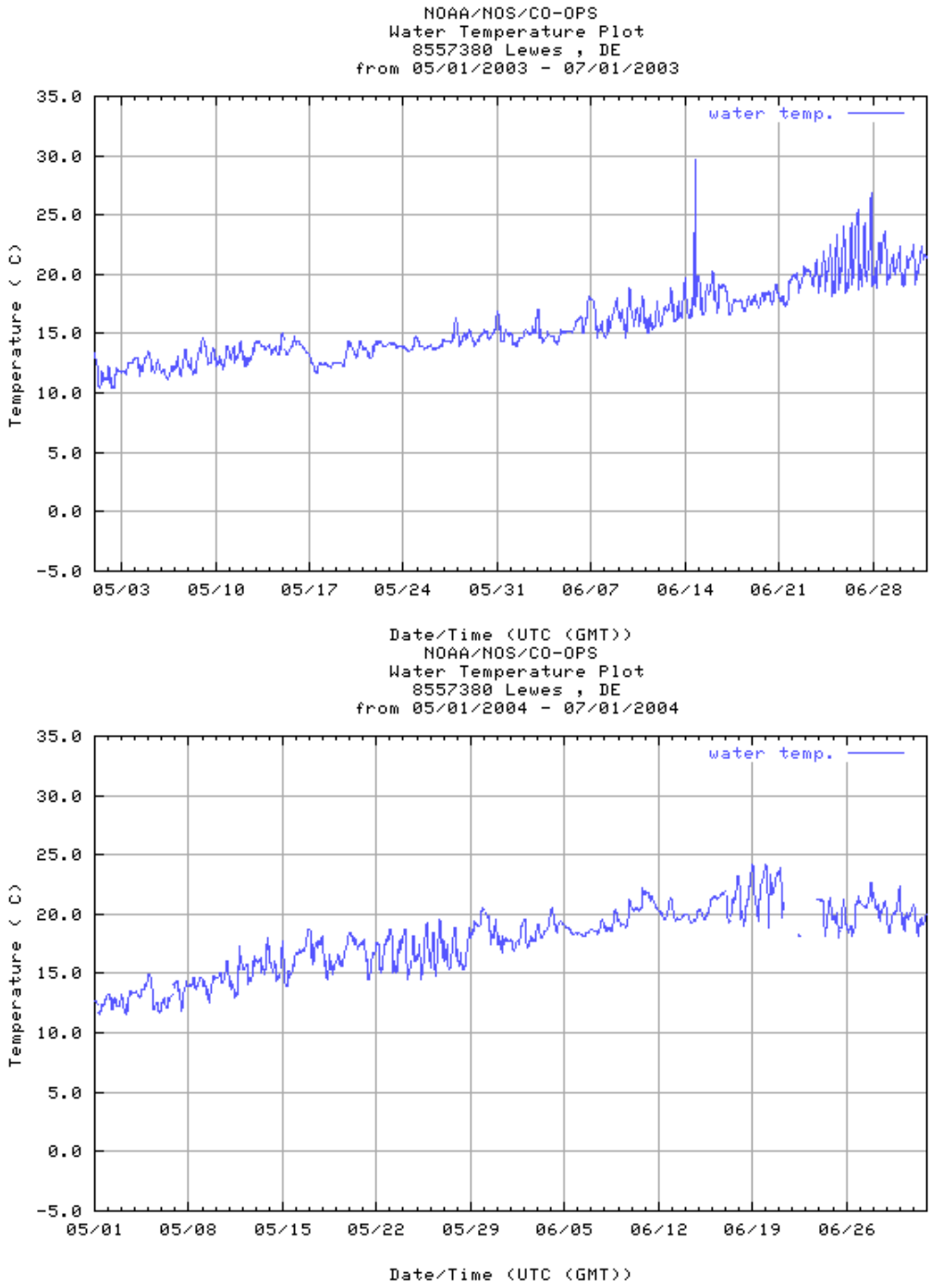
Date/Time (UTC (GMT))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water temp.
Temperature (C)
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Date/Time (UTC (GMT))
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Water Temperature Plot
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water temp.
Temperature (C)
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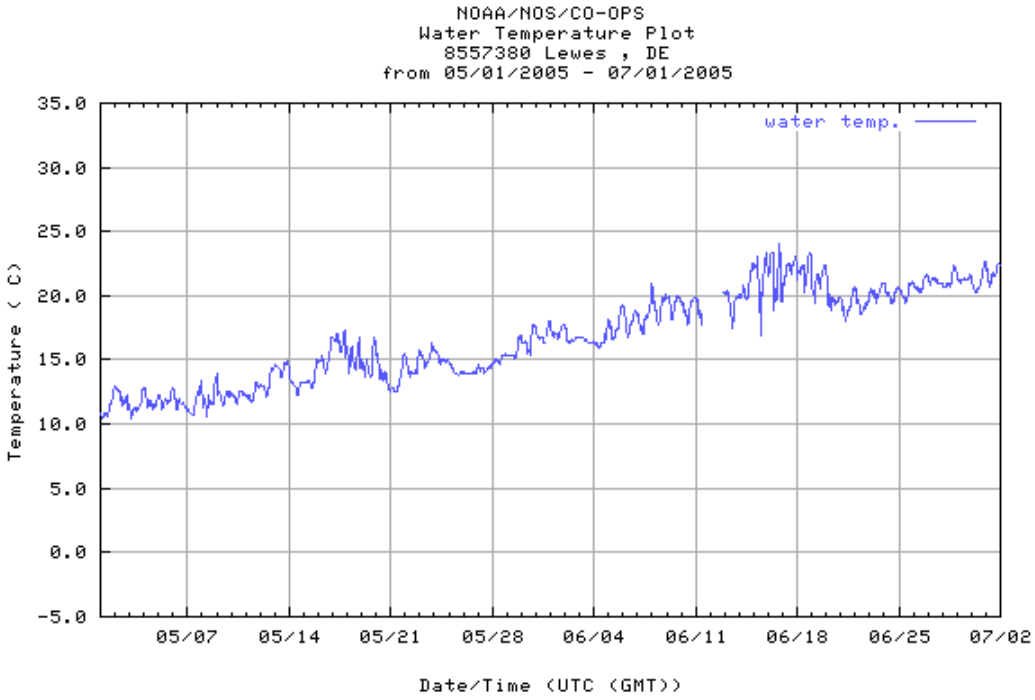
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water temp.
Temperature (C)
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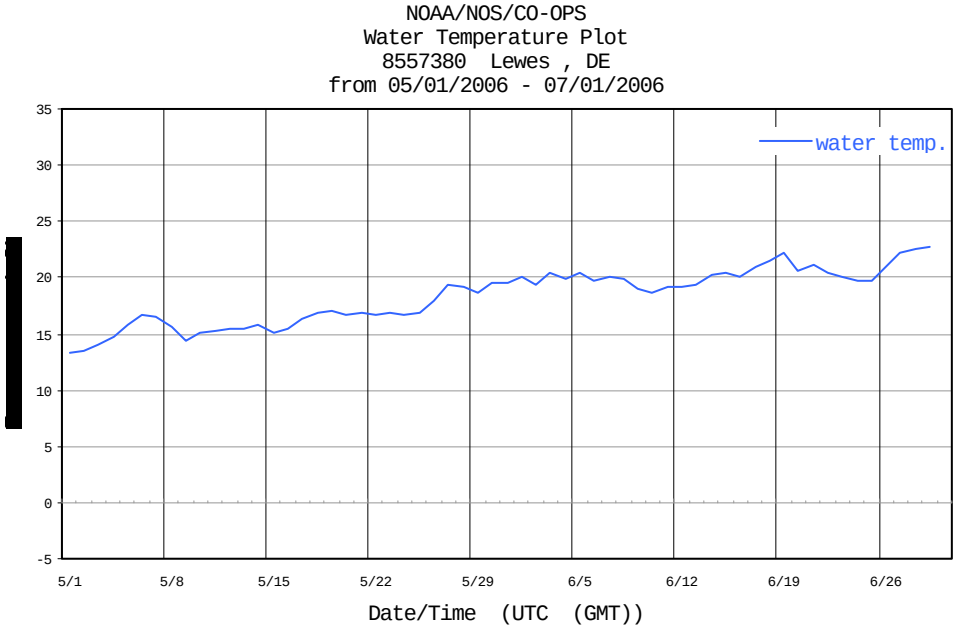
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Water Temperature Plot
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water temp.
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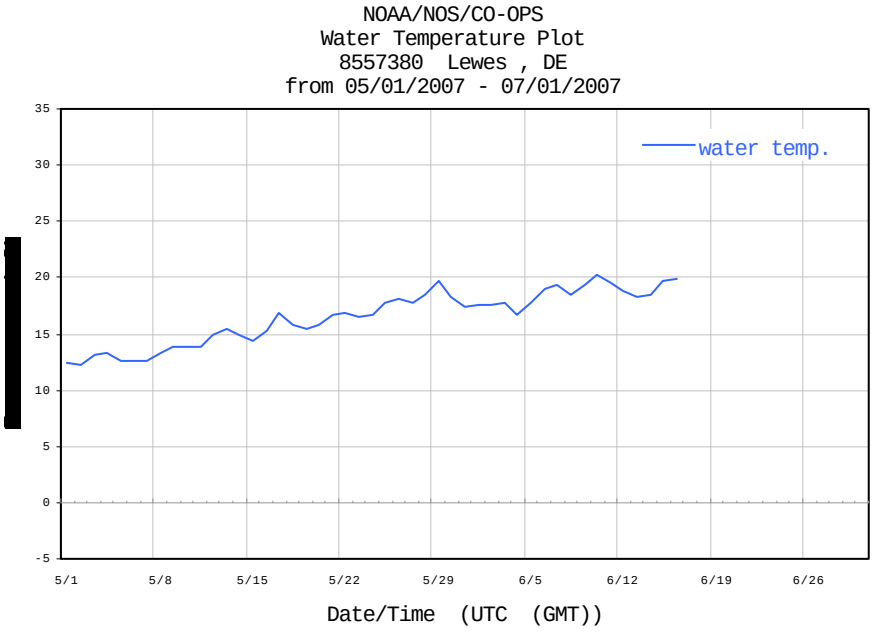
Date/Time (UTC (GMT))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Water Temperature Plot
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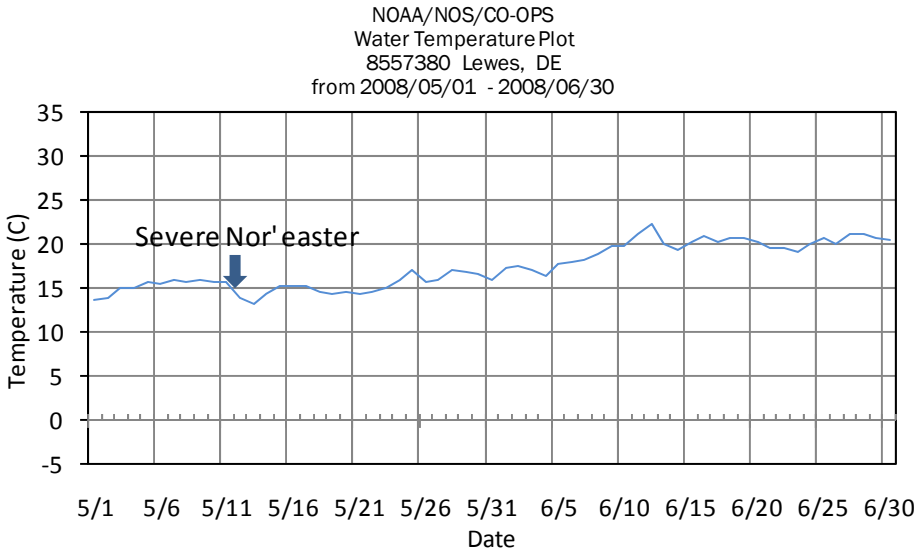
NOAA/NOS/CO-OPS
Water Temperature Plot
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from 2008/05/01 - 2008/06/30
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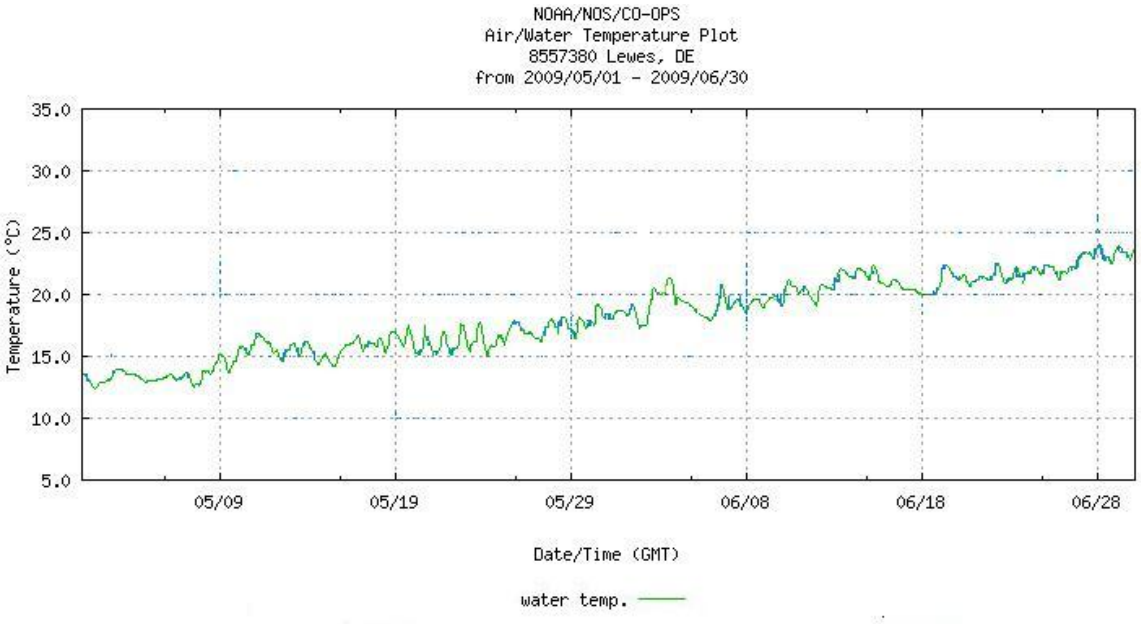
NOAA/NOS/CO-OPS
Air/Water Temperature Plot
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from 2009/05/01 - 2009/06/30
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25.0
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Temperature (°C)
05/09
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06/18
06/28
Date/Time (GMT)
water temp.

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 2009.

State	Beach	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
DE	Bennetts Pier		0.2233	0.6399	0.4713	0.2762	0.5470	0.6992	0.6117	0.5496	0.3726	0.6393
DE	Big Stone	0.7462	0.7290	0.8562	0.6265	0.6370	0.7617	0.8088	1.0896	1.3475	0.7064	0.7852
DE	Broadkill	0.3197	0.0638	0.1170	0.1347	0.2083	0.1741	0.1911	0.1208	0.1775	0.5533	0.2342
DE	Cape Henlopen				0.0857	0.1816	0.1255	0.2694	0.1000	0.0579	0.3000	0.2579
DE	Fowlers	0.7779	0.4933	0.7033	0.2370	0.4532	0.6110	0.2148	0.4077	0.5033	0.5260	0.2057
DE	Kitts Hummock	2.1510	2.5830	2.3545	1.4667	1.5529	1.2394	1.4175	1.7237	1.4394	1.2296	1.4828
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	0.3646	0.6946
DE	Pickering		3.3047	1.6244	1.6950	1.6417	1.6380	1.4708	1.4933	1.6350	1.9908	1.6692
DE	Prime Hook	0.5984	0.1872	0.4446	0.5908	0.4733	0.7596	0.6500	0.7283	1.1088	0.9221	0.6092
DE	Slaughter	1.6190	1.3254	1.0962	0.7265	1.6508	1.5237	0.6805	1.0396	1.2360	1.1005	0.7232
DE	South Bowers		0.9196	0.8433	1.1265	0.4685	0.4796	0.6343	0.7192	1.3026	0.5700	1.0192
DE	Ted Harvey				1.4446	1.9852	1.5220	0.8162	1.4579	1.9279	1.4746	1.1933
DE	Woodland	0.1368	0.1033	0.0292	0.0792	0.0075	0.0012	0.0062	0.2700	0.0312	0.0000	0.0242
NJ	East Point		0.3458									
NJ	Fortescue	0.2473				0.4184	0.5408	0.5818	0.6525	0.1600	0.3267	0.4441
NJ	Gandys	0.4014	0.3922	0.4521	1.4122	0.5498	0.8166	0.8788	1.1652	0.8257	0.2975	1.3051
NJ	Higbees		0.0361					0.1368			0.0321	0.1376
NJ	Highs Beach	0.7892	0.9594	0.7950	0.4685	0.5275	0.6963	0.7583	0.6933	0.7527	0.4558	0.7267
NJ	Kimbles	0.7063	0.8521	0.4773	0.4976	0.4970	0.4054					0.8205
NJ	Norburys			0.4600	0.6242	0.5362	0.6707	0.9391	0.6936	0.4334	0.4133	1.1372
NJ	North Cape May	0.2250	0.0500	0.0904	0.0845	0.1233	0.0200	0.1233	0.0229	0.0417	0.0308	0.0767
NJ	Pierces Point		0.6138		0.6730	0.7300	0.9602	0.8275	0.7447	0.9410	0.7123	1.2721
NJ	Raybins	0.0259										
NJ	Reeds	0.3808	0.6468	0.4049	0.8768	0.8225	0.4162	0.2398	0.9650	0.3050	0.3404	1.0676
NJ	Sea Breeze	0.0947	0.1094	0.2991	1.6283	0.3892	0.4275	0.2088	0.8471	0.9250	0.6650	0.7725
NJ	Cape Shore Lab	1.2452	1.3311	1.2775	0.6850	0.6283	0.9042	1.1684	0.8183	1.2610	0.3886	1.1108
NJ	Sunset			0.1139					0.0119	0.0038	0.0097	0.1590
NJ	Townbank			0.7362	0.3958	0.4589	0.2037			0.2883		
NJ	Villas							0.7075	0.4833		0.3431	0.6433