Horseshoe Crab Spawning Activity in Delaware Bay: 1999 – 2014

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

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Summary

- This annual report marks the sixteenth year that the Delaware Bay Horseshoe Crab Spawning Survey has been implemented in a standardized manner throughout May and June in the Delaware Bay.
- Annual coefficients of variation for estimates of female spawning activity were below 14% for the entire series and remained at or below 10% for the last fourteen years. Annual coefficients of variation for estimates of male spawning activity were below 20% for the entire series.
- Female spawning activity in 2014 peaked during the second lunar period sampled (May 23 – May 27).
- The proportion of female spawning activity observed in May 2014 in New Jersey (65%) was similar to the 16-year average for that state (66%) while Delaware (58%) was close to average (59%) as well.
- Percent of female spawning that occurred in May was associated with water temperature (correlation coefficients were 0.58 and 0.63 for DE and NJ, respectively).
- Bay-wide female spawning activity over the past 16 years showed no significant trend; though, the slope was slightly negative (Slope = -0.01, SE = 0.01, 90% CI = -0.02 to 0.01, P = 0.14).
- No significant trends in state-specific female spawning activity were detected; though, the slope in both Delaware and New Jersey was negative (DE: slope = -0.01, SE = 0.01, 90% CI = -0.02 to 0.01, P = 0.11; NJ: slope = -0.01, SE = 0.01, 90% CI = -0.02 to 0.01, P =0.64).
- Bay-wide male spawning activity showed no significant trend from 1999 through 2014; though, the slope was positive (Slope = 0.03, SE = 0.03, 90% CI = -0.03 to 0.10, P = 0.43).

- No significant trends in state-specific male spawning were detected (DE: slope = -0.01, SE = 0.01, 90% CI = -0.02 to 0.01, P = 0.11; NJ; slope = 0.04, SE = 0.06, 90% CI = -0.06 to 0.14, P =0.30).
- Sex ratio in 2014 was 4.3:1(M:F). Sex ratios during the 16 year time series ranged from 3.1:1 to 5.2:1.

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. Data entry is completed by staff from the New Jersey Department of Environmental Protection; 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 bay-wide 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;

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).

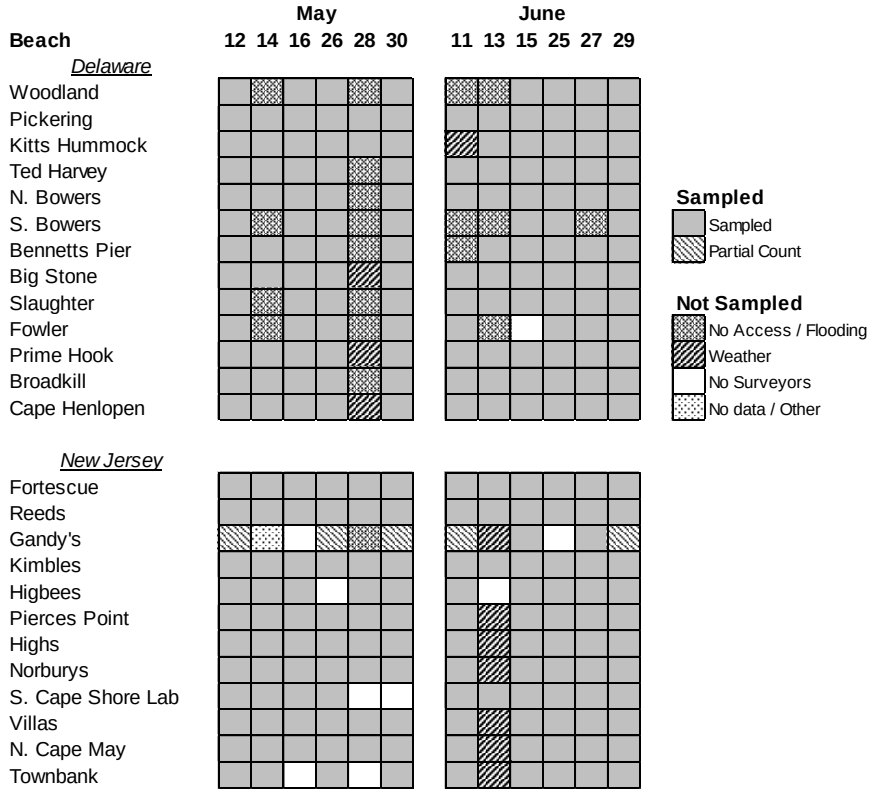
Data Availability

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. Beginning in 2010, the previous software was no longer compatible with updated Windows OS, so the SPAWNr program was developed by Dr. David Smith (USGS) to calculate estimates of abundance. Data used in this report (both estimates and raw data) and the software used to calculate estimates are available by request. Previous reports incorrectly reported standard deviation of spawning activity as the standard error. This error has been corrected and standard deviation, not standard error, will continue to be reported in future years.

Summary Results

Sampling in 2014 was conducted during twelve nighttime high tides from 12 May through 29 June. Twenty-five beaches were sampled in the Delaware Estuary – 13 in Delaware and 12 in New Jersey. The total number of tides sampled over the season was 257, with 43 sampling events missed or canceled (Table 1). Sixteen of the 43 missed sampling events occurred during the second lunar period in May when spawning horseshoe crabs were most abundant. Fourteen of those missed events occurred on the new moon 28 May. Tide heights are greatest on new and full moon dates leading to decreased access of survey areas.

Table 1. Beaches sampled in the 2014 Delaware Bay Horseshoe Crab Spawning Survey.



Temporal Spawning Distribution

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

State-specific female spawning activity peaked in New Jersey and Delaware in the second (May 26-30) lunar period (Figure 1). Sixty-five percent (65%) of the annual female spawning activity in New Jersey and 58% of the annual female spawning activity in Delaware was observed in May (Table 2). The proportion of annual state-specific spawning activity that occurred in May was higher in New Jersey than Delaware for all but three years of the 16 year survey.

Bay-wide female spawning activity peaked in the second lunar period in 2014 (Table 3). This is the twelfth year of the 16 year survey that the second lunar period in May has accounted for the highest spawning activity. This period is critical to shorebird foraging as it coincides with peak stopover period for migratory shorebirds in Delaware Bay (McGowan et.al 2011).

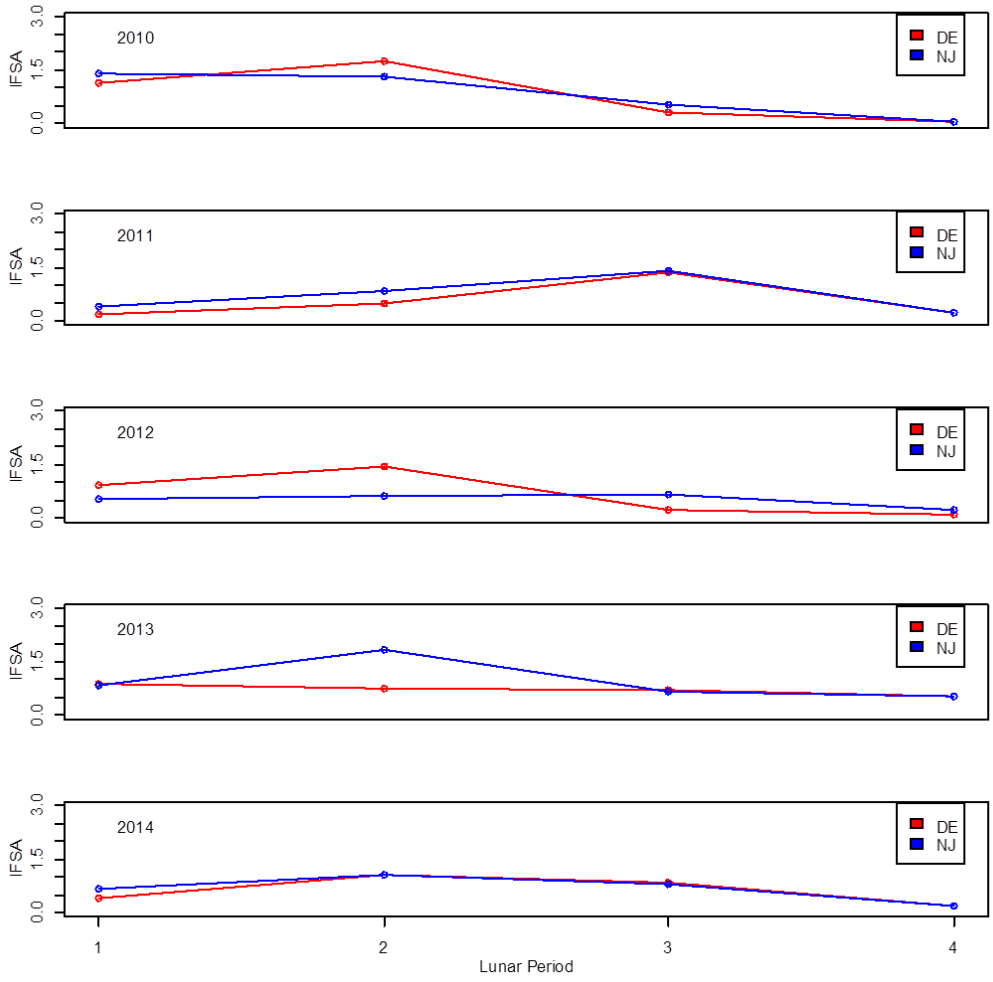


Figure 1. Temporal distribution of female horseshoe crab spawning activity in the Delaware Bay by state for the years 2010-2014. Lunar periods are defined as a 5 day period (sampled day of lunar event and 2 days before and 2 days after) around the new or full moons in May and June.

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 (Station Identification Number 8557380).

	Delaware		New Jersey		
	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
2010	12 May - 16 May	82	25 May - 29 May	88	15.6
2011	30 May - 3 June	52	30 May - 3 June	44	16.0
2012	2June - 6 June	64	18 May - 22 May	92	17.8
2013	23 May - 27 May	71	7 May - 11 May	62	15.3
2014	26 May - 30 May	58	26 May - 30 May	65	15.2

Table 3. Baywide horseshoe crab spawning activity, expressed as mean number of spawning female crabs per m^2, by lunar period for the years 1999 to 2014.

Year	0	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	
2010		1.26	1.52	0.42	0.06	
2011		0.46	0.92	1.00	0.21	
2012	0.18*	0.71	1.02	0.43	0.14	
2013		0.86	1.30	0.68	0.53	
2014		0.54	1.04	0.81	0.18	

**denotes partial survey*

Water temperature is believed to 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 of state-specific female spawning activity in May (r_{DE} = 0.58, P_{DE} = 0.02; r_{NJ} = 0.63, P_{NJ} = 0.01; Figure 2). Delayed spawning in 2003 and 2005 was likely related to water temperatures, as temperatures were not consistently above 15 °C until late May or early June at Lewes, DE. Reduced spawning activity noted during the second lunar sampling period in 2008 coincided with a severe nor'easter that depressed water temperatures. In 2014, water temperatures did not remain consistently above 15°C until after the first lunar period was sampled (May 16).

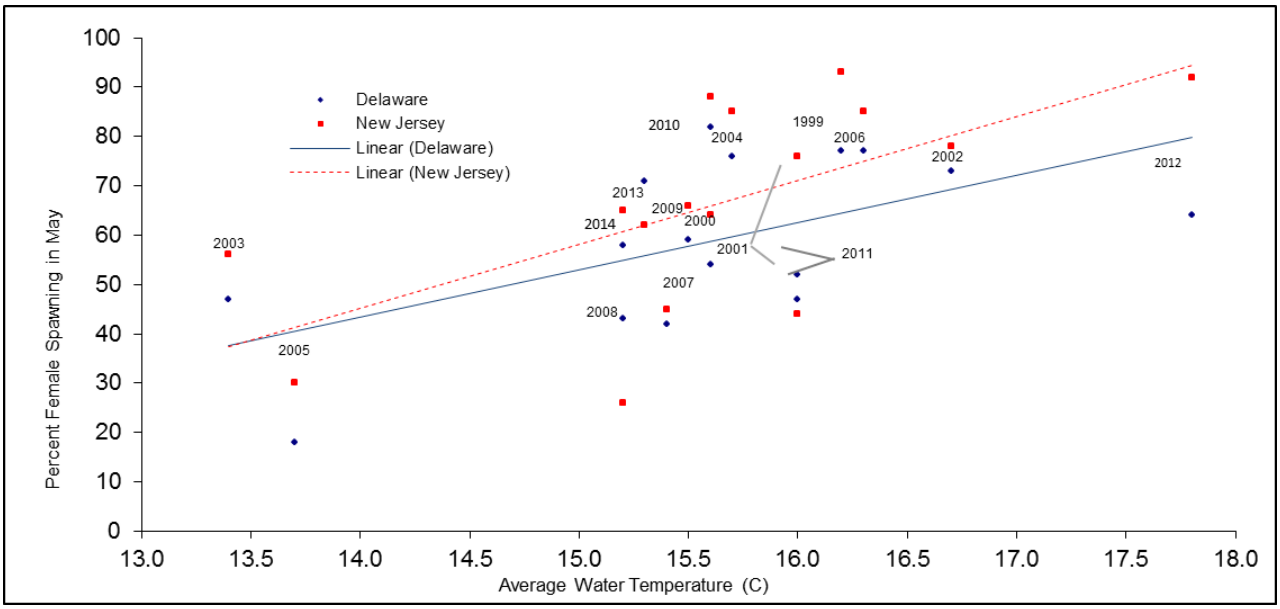


Figure 2. Percent of female horseshoe crab spawning occurring in May by state versus May average daily water temperatures. Water temperatures were recorded by the National Ocean Service at Lewes, DE Station ID 8557380.

State-specific Spawning Activity

Although index values differ by state (Table 4; Figures 3a&b), the trend from the index of female spawning activity in both states exhibited a slightly negative slope, though not significant (DE Slope = -0.01, SE = 0.006, P = 0.11; NJ Slope = -0.006, SE = 0.01, P = 0.64).

Trends in male spawning activity differ between states (Table 5; Figure 4a&b). The index of male spawning activity in Delaware exhibited a slightly negative slope, though not significant (DE Slope =-0.01, SE = 0.001, P = 0.11) while the trend in male spawning activity in New Jersey was slightly positive, though not significant (NJ Slope = 0.04, SE = 0.06, P = 0.46).

Table 4. Indices of female horseshoe crab spawning activity (IFSA), expressed as the mean number of female crabs per m^2, by state from 1999 to 2014.

	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
2010	0.79	0.64, 0.99	13	0.81	0.68, 0.96	12
2011	0.71	0.59, 0.85	13	0.56	0.48, 0.65	12
2012	0.45	0.33, 0.62	13	0.68	0.55, 0.83	12
2013	0.93	0.72, 1.20	13	0.73	0.61, 0.87	12
2014	0.62	0.76, 0.51	13	0.67	0.76, 0.58	12

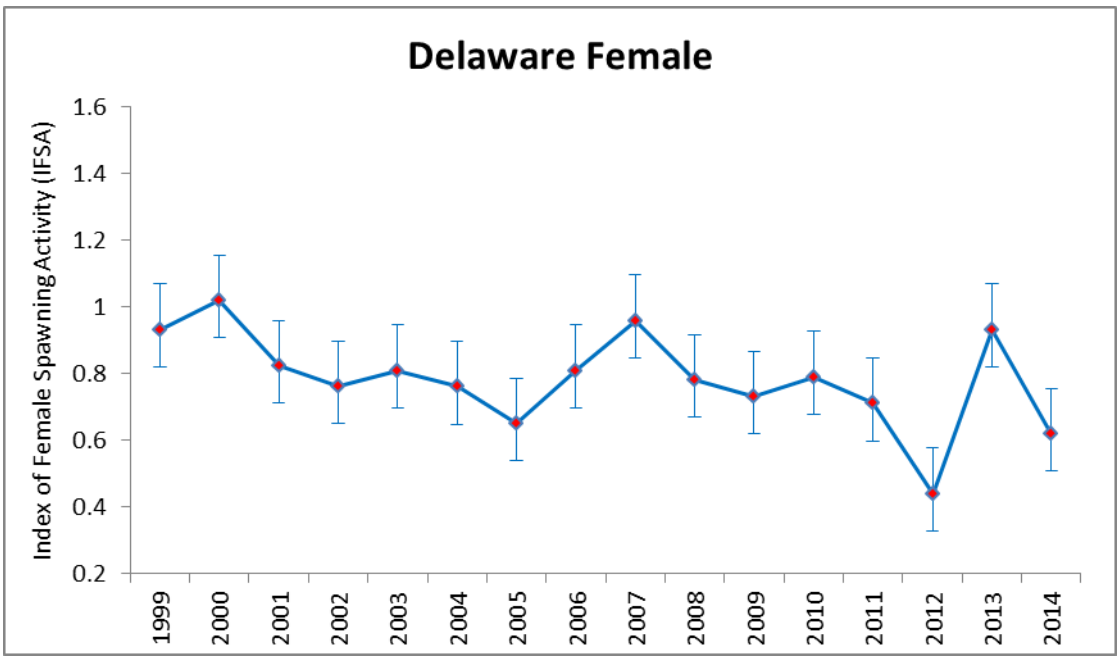


Figure 3a. Index of female horseshoe crab spawning activity (IFSA), expressed as the mean number of female crabs per m^2, for the state of Delaware. Error bars are 90% confidence intervals.

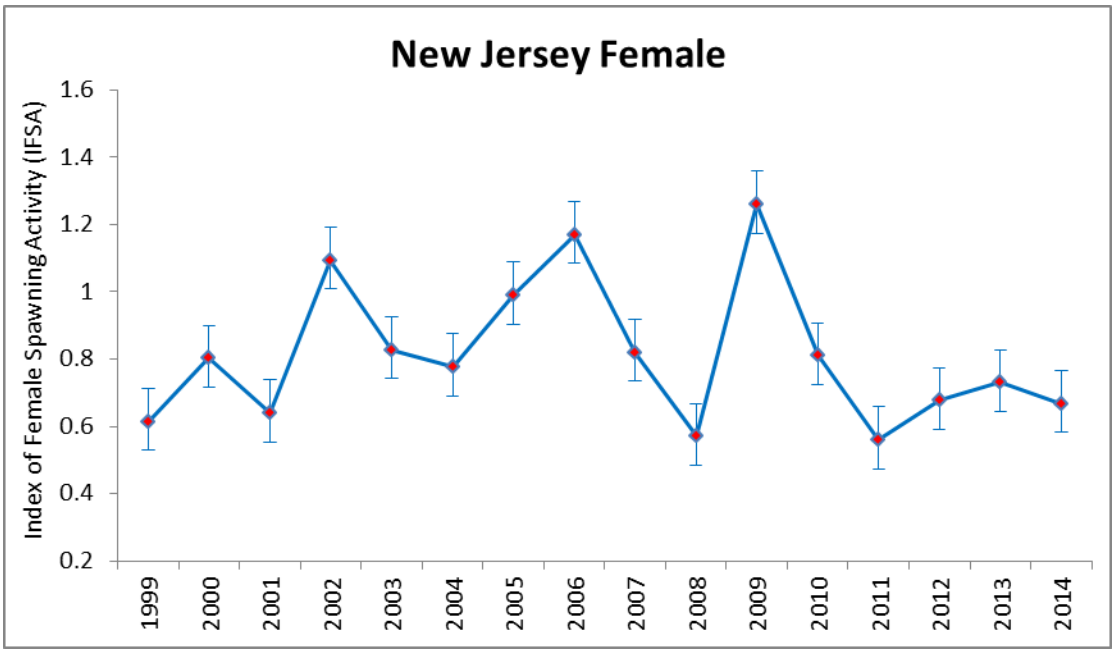


Figure 3b. Index of female horseshoe crab spawning activity (IFSA), expressed as the mean number of female crabs per m^2, for the state of New Jersey. Error bars are 90% confidence intervals.

Table 5. Indices of male horseshoe crab spawning activity (IMSA), expressed as the mean number of male crabs per m^2 per night, by state from 1999 to 2014.

Year	Delaware			New Jersey		
	IMSA	90% CI	Beaches Surveyed	IMSA	90% CI	Beaches Surveyed
1999	3.78	2.65, 5.37	8	1.82	1.24, 2.65	9
2000	3.93	2.76, 5.60	11	2.00	1.55, 2.59	11
2001	2.76	2.02, 3.76	12	2.01	1.50, 2.69	10
2002	2.74	2.13, 3.52	13	3.43	2.91, 4.06	10
2003	2.90	2.23, 3.77	13	2.98	2.67, 3.33	10
2004	2.85	2.27, 3.59	13	3.07	2.64, 3.57	12
2005	2.49	1.99, 3.11	13	4.00	3.30, 4.85	12
2006	3.80	3.03, 4.75	13	4.45	3.84, 5.15	11
2007	4.64	3.81, 5.66	13	4.00	3.22, 4.97	11
2008	4.03	3.16, 5.14	13	2.23	1.86, 2.69	12
2009	3.87	3.08, 4.87	13	5.46	4.74, 6.30	13
2010	3.48	2.77, 4.38	13	3.31	2.75, 3.99	12
2011	4.36	3.49, 5.45	13	2.24	1.93, 2.61	12
2012	2.10	1.48, 3.01	13	2.77	2.15, 3.57	12
2013	3.38	2.61, 4.39	13	2.88	2.35, 3.54	12
2014	2.93	3.71, 2.32	13	2.53	2.98, 2.15	12

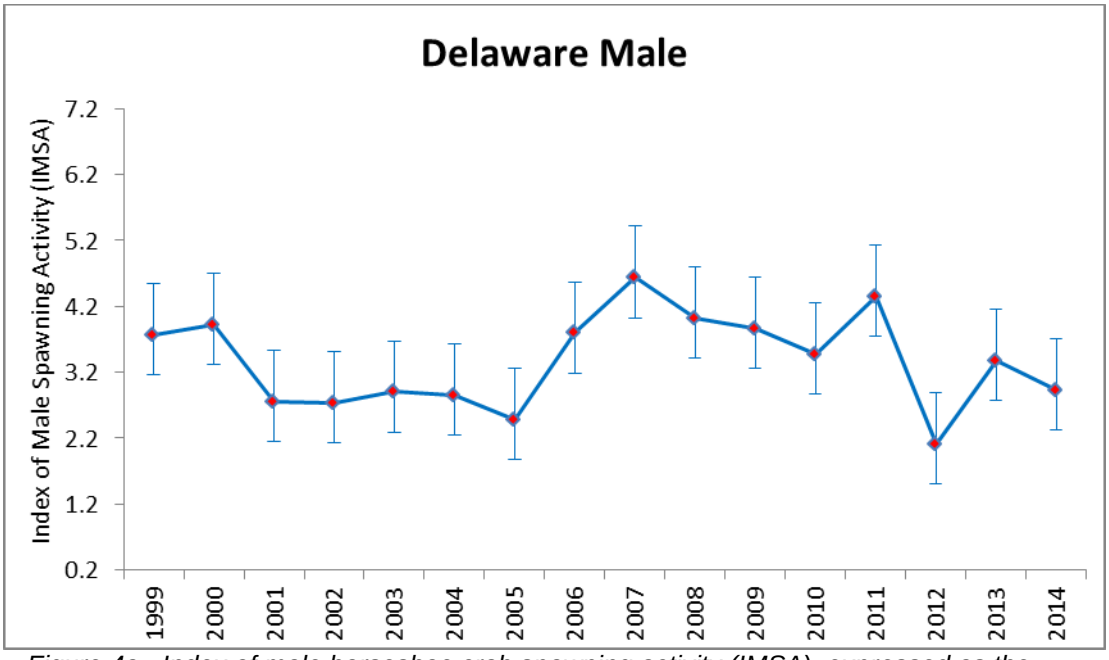


Figure 4a. Index of male horseshoe crab spawning activity (IMSA), expressed as the mean number of male crabs per m^2, for the state of Delaware. Error bars are 90% confidence intervals.

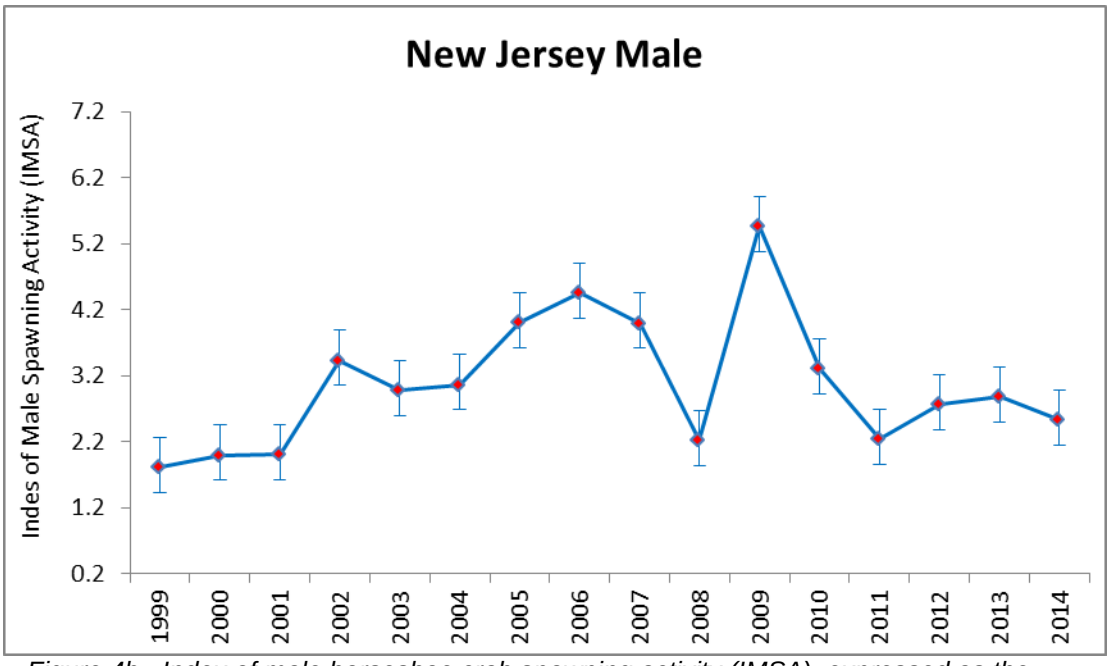


Figure 4b. Index of male horseshoe crab spawning activity (IMSA), expressed as the mean number of male crabs per m^2, for the state of New Jersey. Error bars are 90% confidence intervals.

Bay-wide Spawning Activity - Females

Trends in state-specific female spawning activity were compensatory, as no change in bay-wide spawning activity was detected (Figure 5; Table 6). The regression slope was close to zero (Slope = -0.01, SE = 0.01, 90% CI = -0.02 to 0.001, P = 0.14). Coefficients of variation were below 14% over the entire survey period and at or below 10% since 2002. Female spawning activity by beach for all years is provided in Appendix II. Smith and Robinson (2014) recently used mixed-model trend regression to evaluate beach level trends in spawning density. Their results indicated that, while concentrations at primary spawning beaches tend to be stabilizing, higher numbers of spawning females have become more numerous among ancillary Delaware Bay beaches.

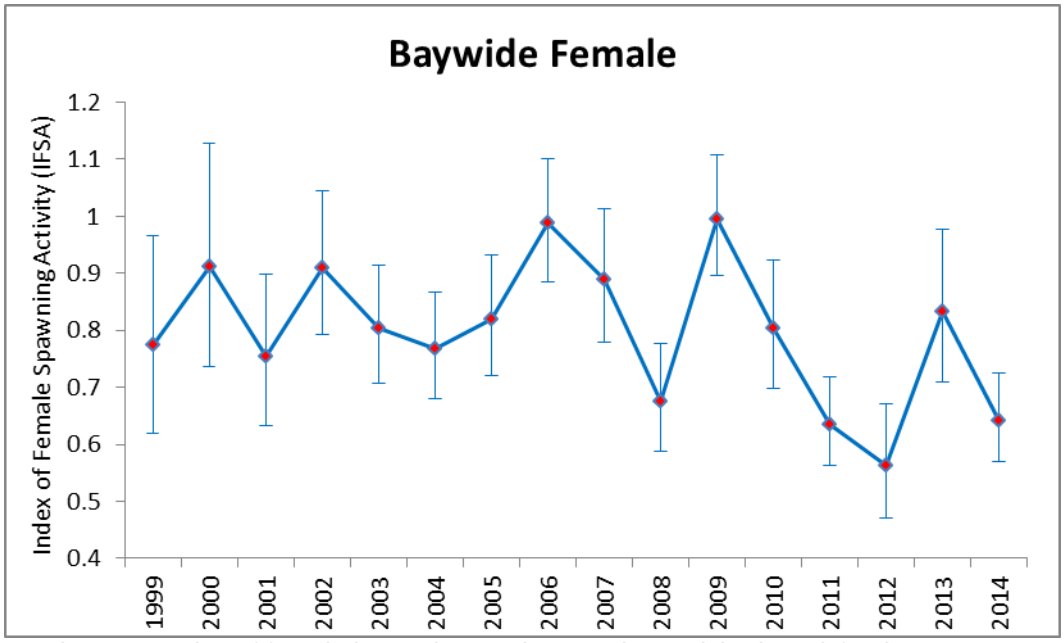


Figure 5. Index of female horseshoe crab spawning activity (IFSA) for the Delaware Bay from 1999 to 2014. Error bars are 90% confidence intervals.

Table 6. Indices of bay- wide male and female horseshoe crab spawning activity (ISA), number of beaches surveyed, standard deviations (SD), coefficient of variations (CV), 90% confidence intervals (CI) and sex ratio for the Delaware Bay from 1999 to 2014.

Year	Beaches Surveyed	Male				Female				Annual Sex Ratio (M:F)
		ISA	90% CI	SD	CV (%)	**ISA**	90% CI	SD	CV (%)	
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
2010	25	**3.39**	2.93, 3.94	0.31	9	**0.80**	0.70, 0.92	0.07	8	4.2
2011	25	**3.31**	2.83, 3.87	0.31	10	**0.64**	0.57, 0.72	0.05	7	5.2
2012	25	**2.44**	1.97, 3.01	0.31	13	**0.56**	0.47, 0.67	0.06	10	4.4
2013	25	**3.14**	2.65, 3.71	0.32	10	**0.83**	0.71, 0.98	0.08	10	3.8
2014	25	**2.74**	3.17, 2.36	0.24	9	**0.64**	0.72, 0.57	0.05	7	4.3

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 cause spawning sex ratios (M:F) to drop and negatively affect spawning and egg fertilization. Annual sex ratios have ranged from 3.1:1 to 5.2:1 over the course of the survey. M:F ratio in 2014 (4.3:1) was above the time series average (3.9:1) (Table 6).

Bay-wide 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 bay-wide male spawning abundance. Male spawning activity decreased slightly, though not significantly (Slope = 0.03, SE = 0.04, 90% CI = -0.04 to 0.10, P = 0.44) from 1999 to 2013 (Figure 6; Table 6). Coefficients of variation for the male component of the survey were below 20% for the entire sampling period.

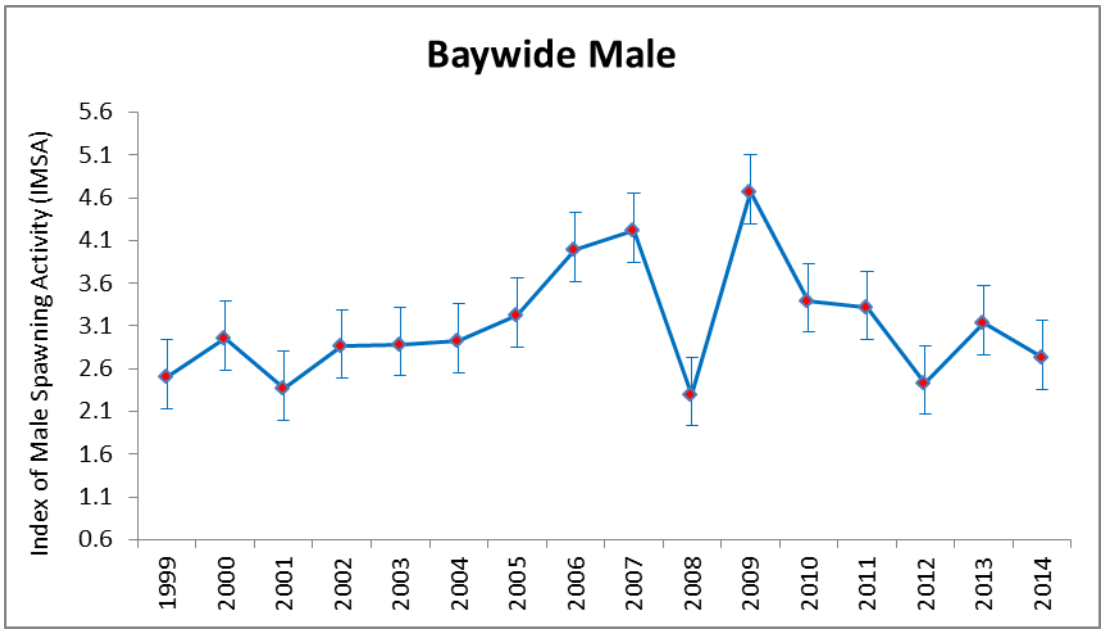


Figure 6. Index of male horseshoe crab spawning activity (IMSA) for the Delaware Bay from 1999 to 2014. Error bars are 90% confidence intervals.

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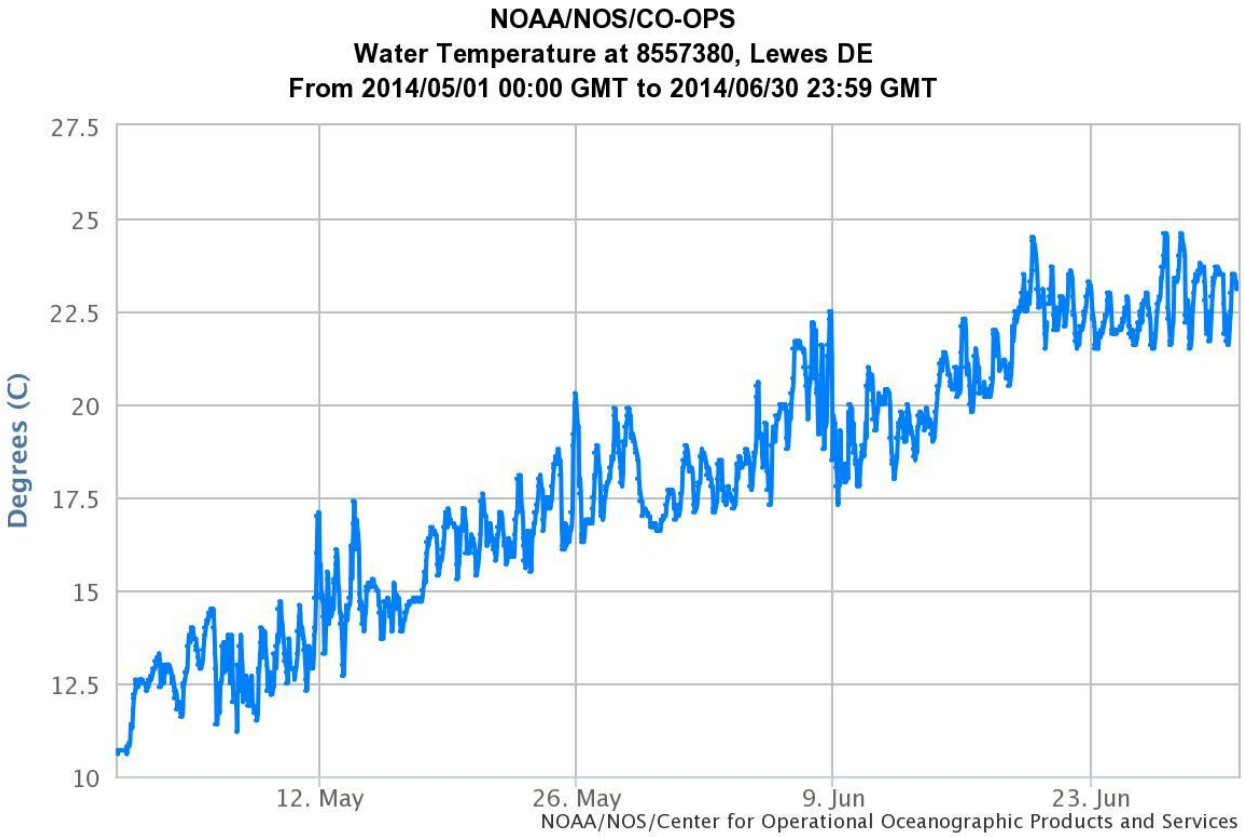
APPENDIX I. Water temperature data from Lewes, DE (Station Identification Number 8557380; Latitude 38° 46.9' N / Longitude 75° 7.2' W) for the 2014. Source: Center for Operational Oceanographic Products and Services (CO-OPS).



APPENDIX II. Index of female spawning horseshoe crabs abundance, expressed as the mean number of female crabs per m^2 per night, for Delaware Bay beaches surveyed from 1999 to 2014.

State	Beach	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
DE	Bennetts Pier		0.22	0.64	0.47	0.28	0.55	0.70	0.61	0.55	0.37	0.64	0.22	0.28	0.32	0.13	0.15
DE	Big Stone	0.75	0.73	0.86	0.63	0.64	0.76	0.81	1.09	1.35	0.71	0.79	0.67	0.86	0.54	0.54	0.61
DE	Broadkill	0.32	0.06	0.12	0.13	0.21	0.17	0.19	0.12	0.18	0.55	0.23	0.49	0.57	0.22	0.57	0.62
DE	Cape Henlopen				0.09	0.18	0.13	0.27	0.10	0.06	0.30	0.26	0.32	0.42	0.30	0.42	0.43
DE	Fowlers	0.78	0.49	0.70	0.24	0.45	0.61	0.21	0.41	0.50	0.53	0.21	0.42	0.13	0.06	0.31	0.17
DE	Kitts Hummock	2.15	2.58	2.35	1.47	1.55	1.24	1.42	1.72	1.44	1.23	1.48	1.30	1.27	0.85	1.91	1.06
DE	Lewes				0.08												
DE	North Bowers	0.88	1.18	1.04	1.21	0.98	0.50	0.60	0.75	1.11	0.36	0.69	0.75	0.49	0.43	1.08	0.29
DE	Pickering		3.30	1.62	1.70	1.64	1.64	1.47	1.49	1.64	1.99	1.67	1.87	1.14	1.42	2.55	0.99
DE	Prime Hook	0.60	0.19	0.44	0.59	0.47	0.76	0.65	0.73	1.11	0.92	0.61	0.92	1.03	0.26	1.12	0.71
DE	Slaughter	1.62	1.33	1.10	0.73	1.65	1.52	0.68	1.04	1.24	1.10	0.72	0.75	1.14	0.47	1.47	0.65
DE	South Bowers		0.92	0.84	1.13	0.47	0.48	0.63	0.72	1.30	0.57	1.02	0.50	0.58	0.54	0.66	0.78
DE	Ted Harvey				1.44	1.99	1.52	0.82	1.46	1.93	1.47	1.19	1.34	1.35	1.23	2.13	1.15
DE	Woodland	0.14	0.10	0.03	0.08	0.01	0.00	0.01	0.27	0.03	0.00	0.02	0.16	0.01	0.08	0.01	0.01
NJ	East Point		0.35														
NJ	Fortescue	0.25				0.42	0.54	0.58	0.65	0.16	0.33	0.44	0.34	0.34	0.73	0.93	0.43
NJ	Gandys	0.40	0.39	0.45	1.41	0.55	0.82	0.88	1.17	0.83	0.30	1.31	1.24	0.25	1.50	1.08	0.54
NJ	Higbees		0.04					0.14			0.03	0.14		0.42	0.06	0.07	0.23
NJ	Highs Beach	0.79	0.96	0.80	0.47	0.53	0.70	0.76	0.69	0.75	0.46	0.73	0.56	0.61	0.68	0.71	0.73
NJ	Kimbles	0.71	0.85	0.48	0.50	0.50	0.41					0.82	0.51	0.33	0.93	0.49	0.47
NJ	Norburys			0.46	0.62	0.54	0.67	0.94	0.69	0.43	0.41	1.14	0.68	0.71	0.78	0.76	0.83
NJ	North Cape May	0.23	0.05	0.09	0.08	0.12	0.02	0.12	0.02	0.04	0.03	0.08	0.02	0.24	0.03	0.06	0.16
NJ	Pierces Point		0.61		0.67	0.73	0.96	0.83	0.74	0.94	0.71	1.27	1.11	0.96	1.13	1.19	1.07
NJ	Raybins	0.03															
NJ	Reeds	0.38	0.65	0.40	0.88	0.82	0.42	0.24	0.97	0.31	0.34	1.07	0.57	0.82	0.86	0.95	0.80
NJ	Sea Breeze	0.09	0.11	0.30	1.63	0.39	0.43	0.21	0.85	0.93	0.67	0.77	1.02				
NJ	Cape Shore Lab	1.25	1.33	1.28	0.69	0.63	0.90	1.17	0.82	1.26	0.39	1.11	0.79	0.80	1.19	0.80	0.57
NJ	Sunset			0.11					0.01	0.00	0.01	0.16					
NJ	Townbank			0.74	0.40	0.46	0.20			0.29			0.31	0.39	0.24	0.52	0.60
NJ	Villas							0.71	0.48		0.34	0.64	0.41	0.53	0.24	0.35	0.71