Seeing the Elephant: Importance of Spatial and Temporal Coverage in a Large-scale Volunteer-based Program to Monitor Horseshoe Crabs

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Seeing the Elephant: Importance of Spatial and Temporal Coverage in a Large-scale Volunteer-based Program to Monitor Horseshoe Crabs

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ABSTRACT: As in John Godfrey Saxe's poem about six blind men and an elephant, conclusions drawn from a monitoring program depend critically on where and when observations are made. We examined results from the Delaware Bay horseshoe crab spawning survey to evaluate the effect of spatial and temporal coverage on conclusions about spawning activity. Declines due to previously unregulated harvest triggered an increase in monitoring. Although we detected no apparent trend in bay-wide spawning activity for 1999–2005, conclusions would have differed depending on where and when observations were made. For example, spawning activity in May during the shorebird stopover was a poor predictor of spawning activity over the whole season. Observations made only during peak spawning incorrectly suggested that spawning activity increased during 2001–2005. Trends at one place in the bay were not indicative of trends for the whole bay. Many natural resource issues begin like the blind men and the elephant with dispute caused by an incomplete picture of the resource. As sufficient time and funds are directed to gathering necessary data using effective sampling designs, a more complete picture emerges.

Caption?

INTRODUCTION

In John Godfrey Saxe's poetic version of a Hindu parable, six blind men each observed a different part of an elephant after which each emphatically and incorrectly inferred the shape of the whole creature (Saxe 1963). One man grasped the elephat's leg and insisted he was hugging a tree trunk. Another imagined a wall. The others sensed a snake, a spear, a fan, and a rope depending on where the blind man stood.

As in Saxe's poem, conclusions drawn from a monitoring program depend critically on where and when observations are made and data are collected. Inference to the whole population can be misleading when spatial and temporal coverage is incomplete (Reece et al. 2001; Dethier and Schoch 2005). This is true for all monitoring programs, but perhaps especially important for volunteer-based programs where there is considerable pressure to play down issues of statistical inference in favor of sampling at times and places that are convenient to volunteers. Involving volunteers in monitoring programs can be beneficial and can provide the means to collect data over large areas and long times for which agency budgets would otherwise not be able to support (Pattengill-Semmens and Semmens 2003). The value of volunteer-based monitoring programs is enhanced considerably when the survey is designed with proper inference as the primary goal (McGarvey and Pennington 2001; de Solla et al. 2005).

A good illustration of the importance of temporal and spatial coverage is the volunteer-based program to monitor horseshoe crab (*Limulus polyphemus*) spawning activity in Delaware Bay (Swan et al. 1993; Smith et al. 2002). Horseshoe crabs emerge onto sandy beaches to spawn in pulses associated with spring tides (Brockmann 2003), and in Delaware Bay they spawn throughout May and June (Smith et al. 2002). The Delaware Bay contains large expanses of sandy beach suitable for spawning habitat. However, horseshoe crabs use beaches in a non-uniform pattern (Botton et al. 1994), and beach selection by spawning animals varies over time. Thus, accurate assessment of the distribution of horseshoe crab spawning depends critically on adequate spatial and temporal coverage of the sampling design.

Horseshoe crabs are central to an environmental conflict involving the interactions of commercial harvesters, the biomedical industry, environmentalists, scientists, and managers (Odell et al. 2005). Monitoring horseshoe crabs has been motivated largely by concern over the effects of previously unregulated harvest on spawning biomass and on the population viability of several species of migrant shorebirds that consume horseshoe crab eggs during their spring stopover in Delaware Bay (Berkson and Shuster 1999; Baker et al. 2004). It is now clear from multiple lines of evidence that abundance of horseshoe crabs declined in Delaware Bay from a peak that occurred prior to 1995 and possibly during the 1980s (ASMFC 2004). That decline was most likely due to the concurrent increase in harvest for use as bait in the eel (*Anguilla rostrata*) and whelk (*Busycon carica* and *Busycotypus canaliculatus*) fisheries. However, since the late 1990s, harvest has been reduced, and the trend in horseshoe crab abundance has been less clear. The uncertainty surrounding the effect of harvest reductions on horseshoe crab abundance has contributed to the environmental conflict. Two horseshoe crab monitoring programs were developed to provide data for population assessment. One is a standardized spawning survey, which began in 1999 (Smith et al. 2002). The other is a coastwide trawl survey, which began in 2001 (Hata and Berkson 2003). Here we focus on the spawning survey to illustrate the importance of appropriate temporal and spatial coverage.

The Delaware Bay horseshoe crab spawning survey has been conducted annually since 1999 and is based on a statistical redesign of previous volunteer-based spawning surveys (Smith et al. 2002). The previous spawning survey, which began in 1990, attempted to survey only during peak spawning within the season (Swan et al. 1993). Extensive spatial and temporal coverage and a substantial increase in sampling effort are the important aspects that differentiate the current survey from previous spawning surveys.

The objective of this article is to analyze results from the seven years of the spawning survey since 1999 to draw conclusions about trends in spawning activity, effectiveness of the survey design, and effectiveness of monitoring programs in general with regard to adequate spatial and temporal coverage. The residence time of migrant shorebirds stopping over in Delaware Bay is much shorter than the horseshoe crab spawning season. Thus, trends in spawning that occurred during the shorebird stopover are examined separately from season-wide trends to assess whether spawning during the stopover is representative of total spawning.

METHODS

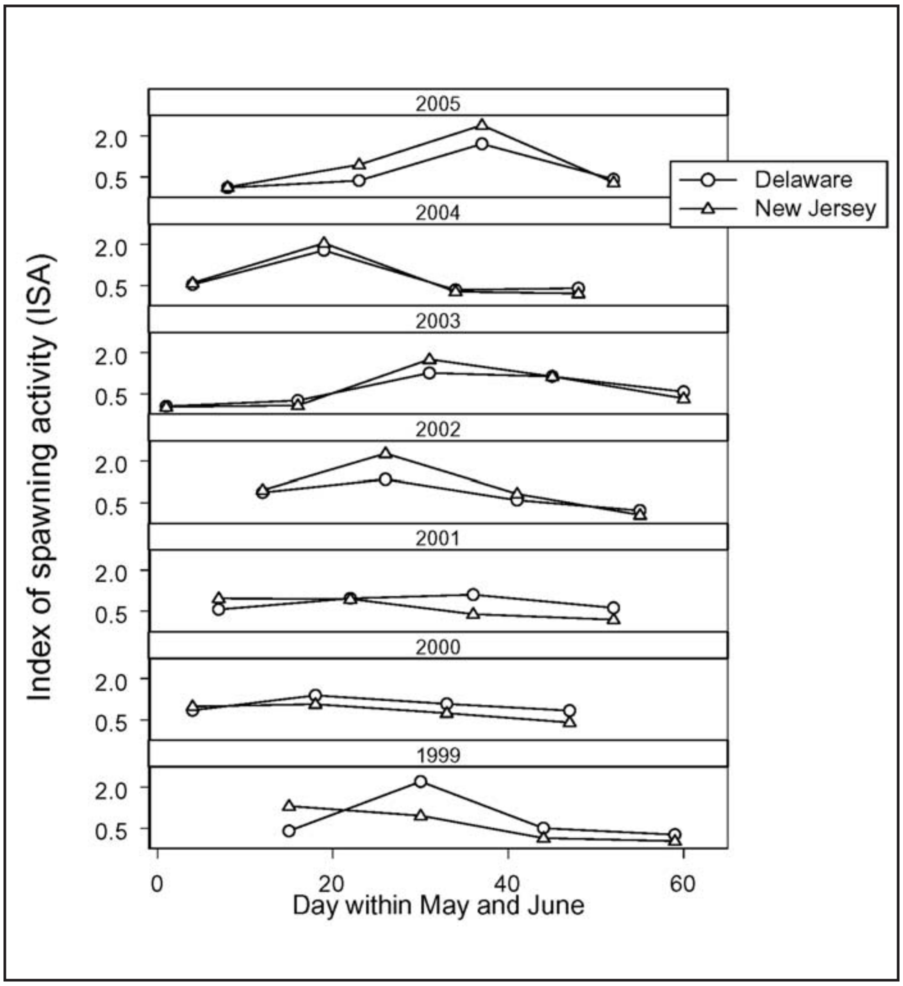
The survey follows a multi-stage sampling design with a selection of beaches, then dates within beach, and finally quadrats on a selected beach and high tide where horseshoe crabs are counted (Smith et al. 2002). Selection of beaches is stratified by state (Delaware and New Jersey), and selection of tides are stratified by the period around the new and full moons in May and June. Only beaches accessible by foot are included in the sampling frame, and a stretch of beach no greater than 1 km is surveyed so that counting does not exceed the time it takes for a female horseshoe crab to spawn (Figure 1). Twelve tides are selected systematically to be 2 d before, the day of, and 2 d after each new and full moon in May and June. The survey takes place on the higher of the diurnal high tides, which is when most spawning occurs in Delaware Bay (Maio 1998). Spawning horseshoe crabs are counted within quadrats (1 m^2) that are located along the beach systematically with two random starts.

Figure 1. Map of Delaware Bay showing accessible sandy beaches. Turn the map 90° clockwise to see the elephant from John Godfrey Saxe's poem.

Both males and females are counted during the survey, but the index of spawning activity (ISA) is calculated using counts of females only. The ISA is the density of females during the higher diurnal high tide within 2 d of the spring tides in May and June. A female will lay multiple nests containing a cluster of eggs on a tide and will spawn on multiple tides (Brockmann 1990; Brousseau et al. 2004). The ISA can be integrated over time as a measure of the cumulative spawning activity within a season. Cumulative spawning and the amount of eggs deposited in the beach during the shorebird stopover are of particular interest for understanding the relationship between horseshoe crabs and shorebirds.

The survey relies on state, federal, nongovernmental organization (NGO), corporate, and citizen cooperation. There are two paid state-level coordinators, one in Delaware and one in New Jersey, who oversee a network of volunteer beach-level coordinators. Training, scheduling, and necessary equipment are provided by the coordinators. Data are entered by New Jersey Department of Environmental Protection, and data analysis is conducted and reports prepared by Delaware Department of Natural Resources and U.S. Geological Survey. The vast sampling effort is conducted by a large contingent of dedicated private citizens, state and federal agencies, corporations, and NGOs. Survey data and software used to calculate estimates are available on the Internet at www.lsc.usgs.gov/aeb/2065/.

Figure 2. Temporal distribution of horseshoe crab spawning activity in the Delaware Bay by state. Spawning was surveyed during the 5-day period centered on the new or full moons in May and June. The index of spawning activity (ISA) is the density of females during the higher diurnal high tide within 2 d of the spring tides in May and June.



RESULTS

First, we examined the variation in timing of spawning within a season. Then, we partitioned the bay into eastern (Delaware) and western (New Jersey) shore and examined the spatial pattern of spawning over years. Last, we combined the results to estimate bay-wide spawning activity over years.

Temporal Spawning Distribution

In general, the temporal pattern has been for spawning to be low in early May, peak in late May or early June, and drop by late June (Figure 2). However, there has been considerable variation in that pattern from year to year. In some years, spawning peaked sharply (i.e., 1999, 2002, 2004, and 2005) while in other years, spawning showed less of a peak and was distributed more uniformly (i.e., 2000 and 2001 especially).

The amount of spawning that occurs in May is of great importance because of the shorebird/horseshoe crab relationship (Baker et al. 2004). Although horseshoe crabs begin to spawn in late spring and into early summer, key migratory shorebirds use Delaware Bay for only a couple weeks during mid-May through early June (Botton and Harrington 2003).

In some years, horseshoe crab spawning was early with a high proportion of spawning occurring in May (i.e., 1999, 2002, and 2004; Table 1). However, in other years spawning was late with a low proportion of spawning in May (i.e., 2003 and 2005 in particular). The percent of spawning in May was higher in New Jersey than in Delaware in all years of the survey. The time of peak spawning in New Jersey was earlier or at the same time as in Delaware (Table 1).

Water temperature may have influenced the timing of spawning. Average daily water temperature readings taken at the National Ocean Service station at Lewes, Delaware, were correlated with the percent of spawning in May (Table 1). Spearman-rank correlations between average daily water temperatures and percent spawning in May were 0.79 (P = 0.04) for spawning in New Jersey and 0.65 (P = 0.12) for spawning in Delaware. In the years with the lowest percent spawning in May (2003 and 2005), average water temperatures did not exceed 14°C during May (Table 1). Daily water temperatures were not consistently above 15°C until late May (i.e., 30 May 2003 and 28 May 2005). In the other years, daily water temperatures were consistently above 15°C by mid-May (i.e., 11 May).

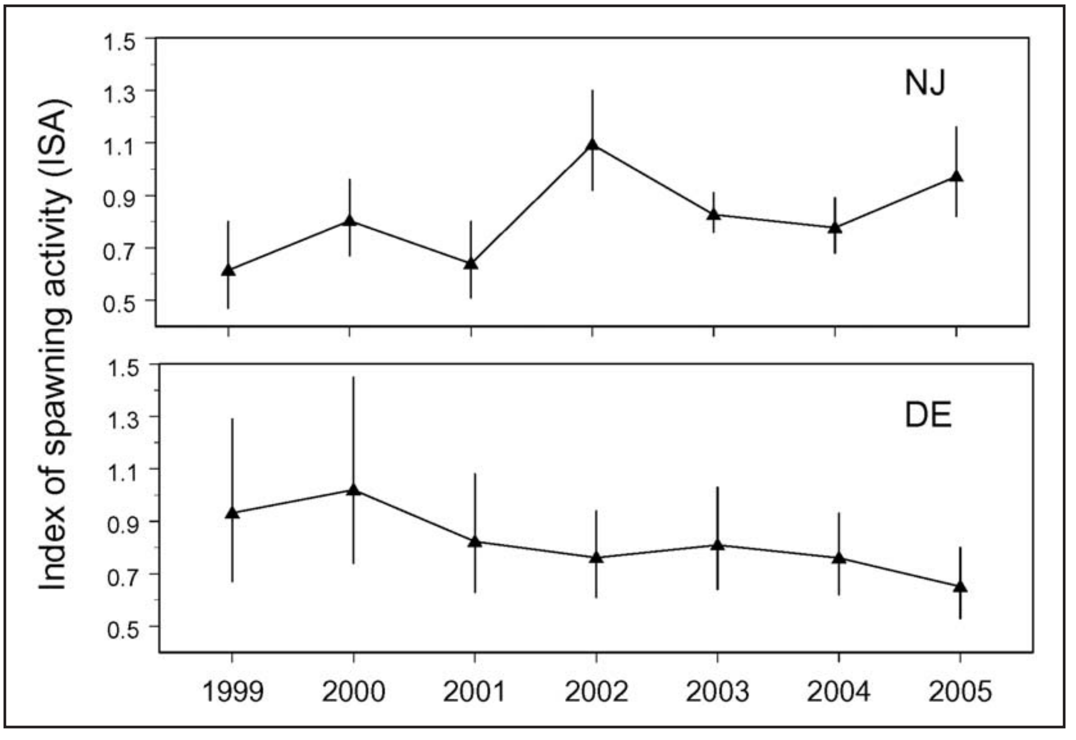
Table 1. Summary statistics reflecting the timing of horseshoe crab spawning in Delaware and New Jersey. Lunar period is the numbered spring tide in May and June. For example, lunar period 1 is the first spring tide in May. Percentages are based on estimates of month-specific index of spawning activity (ISA). Water temperatures were recorded at the National Ocean Service station at Lewes, DE.

Year	Delaware			New Jersey			Average daily water
	Dates of peak spawning	Peak lunar period	% of spawning in May	Dates of peak spawning	Peak lunar period	% of spawning in May	temperature in May (C)
1999	28 May– June	2	77	8 May–12 May	1	93	16.2
2000	16 May–20 May	2	54	16 May–20 May	2	64	15.6
2001	3 June–7 June	3	47	5 May–9 May	1	76	16.0
2002	24 May–28 May	2	73	24 May–28 May	2	78	16.7
2003	29 May–2 June	3	47	29 May–2 June	3	56	13.4
2004	17 May–21 May	2	76	17 May–21 May	2	85	15.7
2005	4 June–8 June	3	18	4 June–8 June	3	30	13.7

State-specific Spawning Activity

Trends in spawning activity differed by state (Figure 3). Spawning activity in New Jersey trended upward from 1999 to 2005, though not significantly (slope = 0.04, SE = 0.030, P = 0.19). Spawning activity in Delaware has trended significantly downward since 1999 (slope = -0.05, SE = 0.01, P = 0.01). The state-specific spawning activity in 2005 (ISA = 0.65 in Delaware and ISA = 0.99 in New Jersey) was a mirror image of spawning activity in 1999 (ISA = 0.93 in Delaware and ISA = 0.61 in New Jersey) when this survey began.

Figure 3. The ISA is the density of females during the higher diurnal high tide within 2 d of the spring tides in May and June.



Baywide Spawning Activity

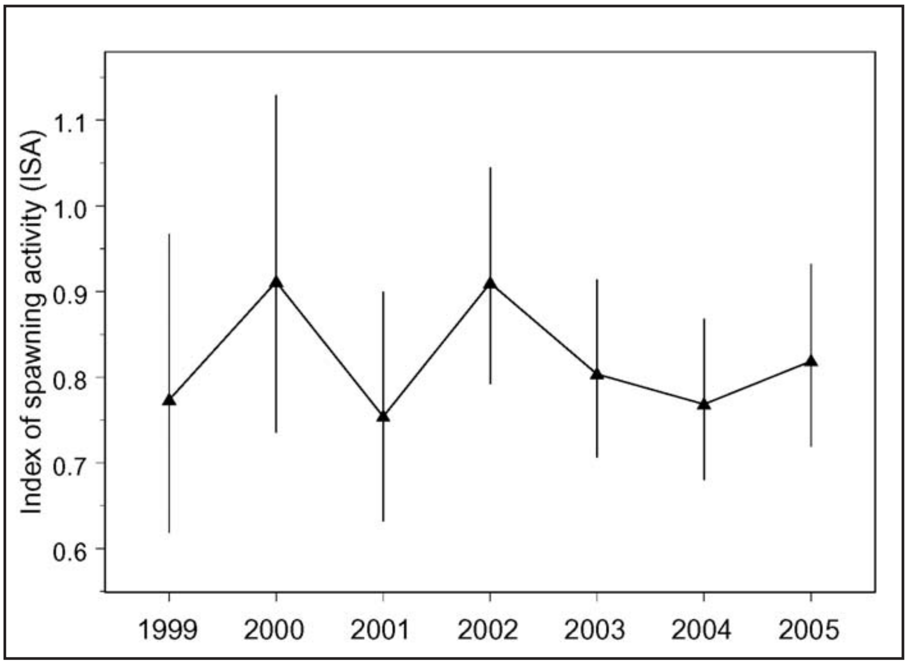
When we integrated data across the bay, we did not detect a change in baywide spawning activity over the period of 1999-2005 (Figure 4; Table 2). The regression slope is close to zero (slope = -0.004, SE = 0.013, 90% CI = -0.031 to 0.023, P = 0.76). The state-specific trends were compensatory and could involve a shift in spatial distribution due to currently unknown causes.

DISCUSSION

Temporal and spatial distribution of horseshoe crab spawning activity was highly variable. If inference about trends in spawning activity were drawn from only certain times and places, then dramatically different conclusions would be reached than if conclusions were based on observations from the whole distribution.

Timing of spawning is an important factor to examine as it is indicative of potential food availability to migratory shorebirds and could affect survival of egg, larvae, and juvenile stages. Age-structured population models indicate that horseshoe crab population growth is sensitive to survival of early life history stages (J. Sweka, U.S. Fish and Wildlife Service, unpublished data). The year-to-year variation was much higher for spawning activity in May than for spawning activity over the whole season (May and June); the SD for spawning activity in May was 5 times the SD for spawning activity over the whole season. Spawning activity in May was not significantly correlated with spawning activity over the whole season (r = 0.27, P = 0.56). Monitoring spawning activity during May is very important because of the relationship between shorebirds and

Figure 4. Index of horseshoe crab spawning activity (ISA) for the Delaware Bay from 1999 to 2005. Error bars are 90% confidence intervals. The ISA is the density of females during the higher diurnal high tide within 2 d of the spring tides in May and June.



horseshoe crabs in Delaware Bay. However, monitoring spawning activity only during the shorebird stopover is a poor measure of spawning activity over the whole season.

Some of the variation in timing of spawning was due to environmental factors, such as water temperature. The relationship between egg development and temperature provides a potential mechanism linking spawning behavior and temperature (French 1979; Jegla and Costlow 1982; Shuster and Sekiguchi 2003). For example, French (1979) reported that eggs incubated at 15°C hatched in 44 days on average; whereas, eggs incubated at 23°C hatched in 26.5 days on average. Thus, there could be a selective advantage to delay spawning until temperatures are sufficient for development. In cold years, horseshoe crabs spawned later than in warm years. There was also an interaction between location in the bay and timing of spawning. Spawning tended to occur earlier along the eastern shoreline than on the western shoreline. The bay to the east of the main channel is wider and shallower than on the west side, which might contribute to warmer water temperatures and thus earlier spawning.

Along with being ecologically important, the timing of spawning can affect inference about population trends. For example, during the period of 1990 to 1999 surveys of spawning in Delaware Bay were designed to measure the peak spawning rather than overall spawning in a given year (Swan et al. 1993). If peak spawning was tracked during the period of 1999 to 2005, the conclusion would be that baywide spawning activity increased from 2001 to 2005 (ISA = 1.0, 1.8, 1.5, 1.9, and 2.0, respectively) and had doubled during that period from 1 to 2 nests per m^2. That conclusion would have been in error. When spawning throughout the season was taken into account, no increase was apparent (Figure 4).

Similarly, trends in spawning activity for a certain part of the bay were not indicative of trends for the whole bay. For example, if only spawning activity along the New Jersey shoreline was observed, one might conclude that spawning activity was trending upward during 1999 to 2005. However, after considering the compensatory downward trend along the Delaware shoreline the overall and proper conclusion would be that spawning activity in the entire bay has been stable during the 1999 to 2005 period (Figure 4). A similar shift in spawning activity from Delaware to New Jersey was observed among adult male horseshoe crabs. Horseshoe crabs do not exhibit fidelity to spawning beaches and migrate between estuaries within regions (King et al. 2005; Swan 2005). Thus, spatial shifts could be dynamic, and historical data supports that. Shuster and Botton (1985) reported that spawning activity was greatest along the New Jersey shore in the early 1980s. During the 1999 to 2001 period, spawning activity was greater along the western shore than the eastern shore. However, since 2001, the spatial pattern in spawning activity has returned to greater spawning in New Jersey than Delaware, which is consistent with Shuster and Botton's (1985) observation.

Table 2. Index of horseshoe crab spawning activity (ISA), standard error (SE), coefficient of variation (CV), and 90% confidence intervals (CI) for the Delaware Bay from 1999 to 2005. The ISA is the density of females during the higher diurnal high tide within 2 d of the spring tides in May and June.

Year	ISA	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	24	0.06	8	0.72, 0.93

The underlying reasons for the spatial shifts are unknown at this time, but could be in response to habitat changes, state-specific fishing pressure or practices, or an unknown biological cycle.

Although the redesigned spawning survey considerably increased the temporal and spatial coverage, some times and places were not included in the sampling frame. For example, beaches were not surveyed during neap tide, only the evening high tide was surveyed, and some beaches were inaccessible. All of these issues were examined as part of the survey design (Smith et al. 2002). The patterns of spawning activity reported by Widener and Barlow (1999) supports the assumptions that trends in spawning during neap and spring tide are similar and that approximately 80% of spawning occurred during the evening high tide. We expect that in some years spawning shifts into neap tide periods due to spring-tide storms, thus contributing to yearly variation in the index of spawning activity.

Although there are differences in the amount of habitat, we estimated baywide spawning activity by weighting data from New Jersey and Delaware equally. Based on interpretation of Digital Ortho Quarter Quads (Delaware 2002 and New Jersey 1997), total shoreline with sandy beach was 90 km in Delaware and 51 km in New Jersey (John Young, U.S. Geological Survey, unpublished data). When restricted to the portion of the bay where most of the spawning occurred, the amount of sandy shoreline was 33 km in Delaware (Slaughter beach to Port Mahon) and 37 km in New Jersey (Norburys to Gandy beach). We use equal weighting because it is straightforward and provides an appropriate measure of baywide spawning activity. In support of the later claim, the overall baywide pattern in spawning activity evident from the spawning survey has been corroborated by trends in relative abundance from the benthic trawl survey conducted during 2000 to 2005 (D. Hata, Virginia Tech, unpublished data).

At the end of his poem, John Godfrey Saxe offers the following moral:

> So oft in theologic wars,
> The disputants, I ween,
> Rail on in utter ignorance
> Of what each other mean,
> And prate about an Elephant
> Not one of them has seen!

The quote leads us to suspect that the nineteenth century John Godfrey Saxe was somehow prescient of twenty-first century environmental conflicts. Nevertheless, we believe the parable's ultimate pitfall is avoidable; no one needs to talk long about an elephant unseen. Heated debate over management of horseshoe crabs has been fueled by an absence of reliable scientific information and fanned by strongly held viewpoints (Berkson and Shuster 1999; Odell et al. 2005). Odell et al. (2005) outlined several biosocial sources for environmental conflict, and the first was the absence of basic scientific information. Although Lackey (2006) points out that scientific information is often a minor consideration in environmental policy debates, misinterpretation of scientific information is, at the very least, unhelpful to conflict resolution and an obstacle to effective decision making. Ultimately, reliable information, like proper inference, depends on proper methodology. Many environmental conflicts begin like the blind men and the elephant with dispute caused by an incomplete picture of the resource. As sufficient time and funds are directed to gathering necessary data using effective sampling designs, a more complete picture emerges.

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