Chapter 31
Horseshoe Crab Research in Urban Estuaries: Challenges and Opportunities

Jennifer H. Mattei, Mark L. Botton, Mark A. Beekey, and Christina P. Colón

Abstract Horseshoe crabs rely on estuaries for food resources, places to spawn and for larvae and juveniles to develop and grow. Many of these estuaries are becoming increasingly urbanized and dominated by human activity. An urban estuary is characterized by armored shorelines, high nutrient loads, large fluctuations in algal and bacteria populations, increased levels of pollutants like heavy metals and pesticides, and seasonally low oxygen levels and pH. While urban estuaries are challenging for horseshoe crab survival and to researchers trying to study them, there are also opportunities for involving the public in research and increasing public awareness of the importance of the conservation and survival of horseshoe crabs. Two recent studies in New York and Connecticut have involved citizen scientists to tag and gather valuable data on horseshoe crab population dynamics. It has been discovered that there is very low recruitment of new adults into the two urban estuaries studied and that spawning populations of horseshoe crabs are relatively low when compared to less disturbed more rural estuaries.

Keywords Urban estuary • Eutrophication • Acidification • Armored shoreline • Jamaica Bay NY • New Haven CT • Citizen science • Civic Engagement • Volunteer-based projects • Carapace condition

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31.1 Introduction

Both horseshoe crabs and human beings are estuarine-dependent species. Horseshoe crabs use estuaries as spawning and feeding habitat for adults (Brockmann 2003; Botton 2009), a site for egg development (Botton et al. 2010), and as juvenile nursery areas (Botton et al. 2003; Carmichael et al. 2003; Burton et al. 2009). Humans depend on estuaries for many ecosystem services including transportation, recreation, food and water resources, waste disposal, industry, energy needs and community development (Mattei 2005; Barbier et al. 2011). With some 123.3 million people in the US (39 % of the total population) living in coastal counties (National Ocean Service 2014) and well over three billion people worldwide found living within 200 km of a coastline (Creel 2003; Valiela 2009), it was inevitable that horseshoe crabs and humans would come into conflict over the use of the coastal zone. Sea walls, bulkheads, groins, and jetties, ubiquitous coastal protection measures used in virtually all of our urban estuaries, may impede or preclude access by horseshoe crabs to critical beach spawning habitats (Botton 2001; Chiu and Morton 2003; Jackson and Nordstrom 2009; Tsuchiya 2009; Jackson et al. 2010). Water quality in urban estuaries is commonly affected by municipal, industrial, and non-point source pollution carried by stormwater runoff and ground water discharges. Pollutants often include multiple biotic stressors such as heavy metals, pesticides, pharmaceuticals, plastics, and raw sewage. Pollution can change nutrient cycling which may result in large fluctuations in algal and bacterial populations and seasonal decline in dissolved oxygen levels, i.e. hypoxia (Varekamp et al. 2014). These common conditions of urban seas may have adverse effects on the developmental success of horseshoe crab eggs, growth and survival of juveniles, and survival of adults (Botton and Itow 2009; Beekey and Mattei 2015).

Much of the literature on American horseshoe crabs is based on studies conducted in less urban, i.e., less disturbed habitats, such as lower Delaware Bay (Shuster and Botton 1985; Smith et al. 2002), Cape Cod (Barlow et al. 1986), or the Gulf Coast of Florida (Rudloe 1980; Brockmann and Johnson 2011), with far fewer studies from urban sites (e.g. Jamaica Bay, New York, Botton et al. 2006a and New Haven Harbor, Connecticut, Mattei et al. 2010; Beekey et al. 2013). With respect to many biotic and abiotic characteristics, urban estuaries significantly differ with the intensity of coastal development and accompanying issues pertaining to habitat and water quality, access to research sites, and anthropogenic influences on research sites. Urban estuaries present challenges to both horseshoe crabs and those who study them, but we suggest that they offer opportunities that in many cases can enhance data collection and ultimately conservation of a species under threat living close to our cities. Here, we discuss the challenges and opportunities that urban estuaries present for conducting research on horseshoe crabs.

31.2 Urban Estuaries

By definition, urban ecology concerns the study of organisms and their interactions in mainly terrestrial sites or within watersheds based on the predominance of buildings and infrastructure, coupled with dense human populations (McDonnell and Pickett 1990; Mayer et al. 2010). In contrast, most ecological studies are concentrated in less urban or rural areas, where sites have little or no human infrastructure and low human population density. Comparative studies are based on a gradient of human impact. Due to the very nature of ecosystems having diffuse boundaries, very few to no habitats would be considered pristine or without some human influence (Ellis et al. 2013). Many papers have been published based on comparing and contrasting ecological processes on this urban-rural gradient (Niemela et al. 2011). It would logically follow then that urban estuaries and seas are defined by the comparatively high level of human use and development of the surrounding areas and would also warrant study and comparison to less urbanized estuaries. When studying horseshoe crabs or other urban estuarine biota, many factors can lead to changes in population dynamics, species behavior, health and interactions with other species that may differ from their counterparts in rural estuaries (Mattei et al. 2010).

Urban estuaries differ substantially from more rural estuaries by the type of human disturbance and the level of disturbance. For example, as human populations grow in cities along the coast, the volume of nitrogenous waste and carbon load increases proportionately. Discharge from wastewater treatment facilities supplies over 53,000 tons per year of nitrogenous waste products to Long Island Sound (Lopez et al. 2014). In fact, the watershed for the Sound includes five states, all of which compounds the waste problem. Other sources of nitrogenous waste or excess nitrogen include: effluent from industrial facilities, fertilizers from farms, lawns, and gardens, as well as waste produced by domesticated animals (from cows to cats and dogs); all eventually ending up in our urban seas like Jamaica Bay (JB) and Long Island Sound (LIS). One of the more biologically deleterious effects of nitrogenous waste and macronutrient loading is hypoxia. Nitrogenous waste has a fertilizing effect on JB and LIS waters, causing algal blooms. As the algae die and sink to the bottom, bacteria decompose the organic matter and deplete the oxygen within the bottom two thirds of the water column. Surface waters have dissolved oxygen because of the close contact with the atmosphere. Hypoxia usually occurs in the western half of LIS including New Haven Harbor (NHH) and in the upper eastern sections of JB during the months of July through October (Wallace et al. 2014). Most of the organisms (fish, crabs, shellfish, and other invertebrates) either die or leave the affected area (Lopez et al. 2014; Varekamp et al. 2014). Remarkably, horseshoe crab adults and juveniles can survive very low levels of dissolved oxygen, and large die-offs in Western LIS have not been reported (Botton et al. 2010, Penny Howell, Connecticut Department of Energy and Environmental Protection, pers. comm.). In addition to hypoxia and its negative impact on the biodiversity of LIS, pathogens are also carried into LIS from untreated waste water (Lopez et al. 2014). Eutrophication and increases in green algal blooms may also lead to disease outbreaks in horseshoe crab populations (Nolan et al. 2009; Braverman et al. 2012). Various heavy metals in differing types and amounts are also present in urban estuaries (Varekamp et al. 2014). These pollutants may be tolerated by horseshoe crabs, but it certainly can decrease the quality of the habitat and quantity of food resources (Varekamp et al. 2014).

Carbon dioxide (CO_2), another byproduct of eutrophication and decomposition can substantially reduce the pH of the urban estuary (Wallace et al. 2014). This acidification is in addition to general ocean acidification from increasing atmospheric CO_2 (Doney et al. 2009). In a recent study of Northeastern urban estuaries including JB and LIS, waters that exhibit hypoxia also during the late summer and fall experience a drop in pH from 8.2 to 7.2 on average over a 2 year study period (Wallace et al. 2014). The acidification is from the carbonic acid produced by bacteria during decomposition of organic matter and from atmospheric CO_2 (Feely et al. 2010). It was also recently discovered that aragonite, a polymorph of calcium carbonate, which is important to shellfish development, is also under-saturated in JB and NHH (Wallace et al. 2014). This will directly impact shellfish reproduction and survival, which in turn will affect the availability of food resources for horseshoe crabs (Botton 2009; Wallace et al. 2014). Calcium carbonate has not been found in large quantities in the exterior shell of horseshoe crabs; however, aragonite minerals may be important in the formation of the interior core of the horseshoe crab shell during growth and development (Chen et al. 2008). The effects of under saturation of these compounds in estuaries on *Limulus* development have not been reported and are in need of further study.

Urban estuaries have high sediment loads, algal and microbe densities, which results in loss of water clarity and light penetration (Valiela 2009). Male horseshoe crabs usually find females during mating season by sight (Barlow and Powers 2003; Brockmann and Smith 2009). The eutrophication of urban estuaries could negatively affect horseshoe crabs by reducing visibility. In low density populations in murky urban waters, males may be unable to see females, which could leave some females single, resulting in lower reproductive output of the population (Mattei et al. 2010; Beekey and Mattei 2015).

Urban estuaries, adjoining harbors and beaches experience artificial light pollution. A survey of nightly light pollution in coastal areas in 2010 revealed that Asia and North America had the second and third largest areas affected, respectively, worldwide (Davies et al. 2014). Known and potential impacts on estuarine biota include disruption of reproductive cycles, decreasing survival and changing predator-prey interactions (Becker et al. 2013; Davies et al. 2014). How light pollution may affect horseshoe crab behavior and survival is unknown. However, there is some evidence that changing the light exposure may affect either circadian or circatidal rhythms in some animals during lab experiments (Chabot and Watson 2010).

Physical alterations of urban estuaries are extensive (Defeo et al. 2009). Often the natural habitats like oyster reefs and beds, eel grass and saltmarsh grasses are removed or buried with sediments and organic matter from human activity that includes dredging and dumping (Weigold and Pillsbury 2014). To prevent erosion, the shoreline is often armored. Seawalls, bulkheads, large rip-rap, breakwaters and groins may hold sediments in the short run, but in the long run numerous problems have been observed. An armored shoreline cuts the connection between the land and the sea that many organisms rely on to survive including shorebirds and horseshoe crabs (Dugan et al. 2008). The armoring reflects the wave energy back onto the beach and causes vertical erosion, loss of beach sediments, organic material and intertidal habitats. Loss of spawning beaches from bulkhead expansion along many urban coastlines in Japan and other countries is directly correlated with the decline of Asian horseshoe crab species (Shuster and Sekiguchi 2009).

In spite of the challenges imposed by sharing the estuarine habitat with humans, horseshoe crabs are remarkably resilient animals that appear to thrive or are at least tolerant of our polluted urban estuaries. Studies of horseshoe crabs in urban estuaries have provided important insights into possible reasons for the evolutionary success of the group. For example, although horseshoe crabs obviously did not evolve in the presence of man-made pollutants except in the last 100 years, fossil evidence suggests that they have always tracked the presence of shallow-water marine habitats (Rudkin and Young 2009; Kin et al. 2013) and have possibly spawned and deposited eggs intertidally (Diedrich 2011) as they do today. Horseshoe crab spawning occurs in habitats that require their eggs, embryos and larvae to tolerate wide swings in environmental conditions (e.g. Botton et al. 2010). Horseshoe crab eggs, embryos and larvae have been shown to be highly tolerant of the typical organic and inorganic pollutants found in urban estuaries, which is consistent with their overall physiological plasticity (Botton and Itow 2009). They have biochemical defense mechanisms (e.g. stress proteins or Heat Shock Proteins) that help guard against damage to physiologically important proteins that might be caused by extremes in temperature (Botton et al. 2006b) and salinity (Greene et al. 2011). So, perhaps part of the explanation for pollution tolerance in horseshoe crabs is related to these kinds of adaptations to survive environmental fluctuations in general.

All coastal estuaries will be affected in one way or another by sea level rise and other factors associated with global climate change. During our current age of human domination, known as the Anthropocene, species that are generalists, which have a wide tolerance to temperature changes, salinity changes, and have variable diets, will have a good chance for survival. However, there may be a tipping point in urban estuaries, where multiple factors become too harsh for horseshoe crabs to survive. As this occurs, the results would be a reduction in the horseshoe crab population size with a patchy distribution similar to what we observe for *Tachypleus* in Southeast Asia (Nishida and Koike 2009; Shin et al. 2009; Yang et al. 2009).

Each summer our urban estuaries become ‘hot, sour, and breathless’ (i.e. increase in temperature, lower pH, and hypoxic), and adding each of the additional stressors discussed above could lead to synergistic effects that cause losses in biodiversity. The need for management of human derived pollution could never be more imperative (Gruber 2011; Wallace et al. 2014).

31.3 Study Areas

Jamaica Bay (Fig. 31.1) is located almost entirely within the New York City limits. It occupies an area of 101 km^2 and has a mean depth of 4.0 m. The estuary is highly eutrophic and receives the majority of its freshwater and pollutant inputs from water treatment plants, storm sewers, and combined sewer overflows (O'Shea and Brosnan 2000; Beck et al. 2009). Jamaica Bay is experiencing rapid loss of wetlands and beaches, attributed to global sea level rise and local processes including land subsidence (Gornitz et al. 2002; Hartig et al. 2002). The hydrodynamics within Jamaica Bay have been affected by extensive dredging for land reclamation, including the construction of Floyd Bennett Field and JFK International Airport, and the dredging of navigational channels. Other large-scale disturbances to Jamaica Bay include extensive bulkheading throughout the bay, and the construction of several sanitary landfills along the northern margin. Despite these major perturbations, Jamaica Bay is one of the most important spawning locations for horseshoe crabs in New York State's marine district, with especially high densities occurring at Plumb Beach, Dead Horse Bay, and Big Egg (Sclafani et al. 2009). Smaller, more isolated patches of sand that are interspersed within regions of armored shorelines can also attract high densities of spawning crabs (Botton et al. 2006a).

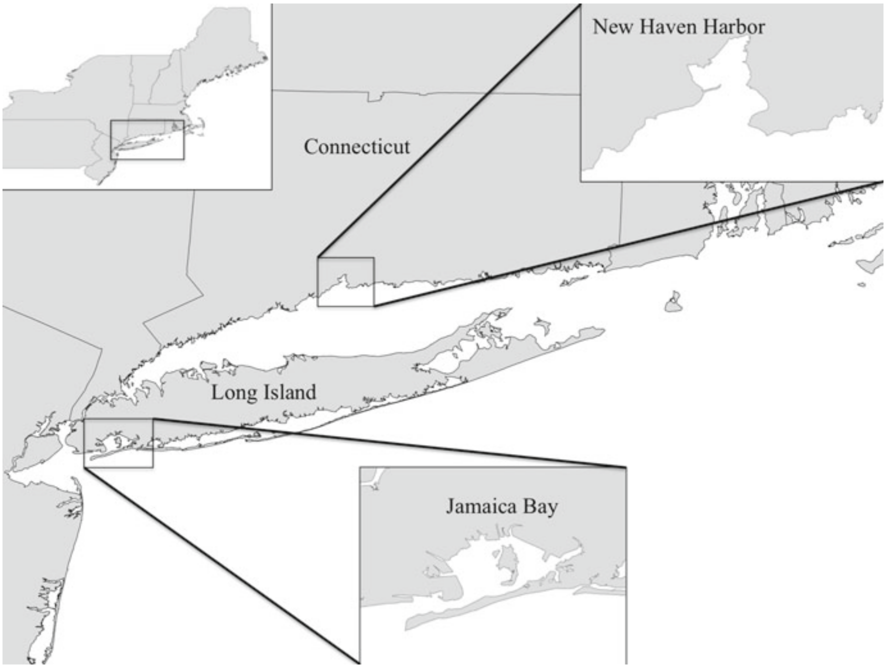


Fig. 31.1 A map of two urban estuaries, Jamaica Bay, New York and New Haven Harbor, Connecticut

New Haven Harbor, located on the north shore of Long Island Sound (Fig. 31.1), is an active port that has been heavily impacted by many decades of industrial activity along the shoreline and within the watershed (Rozan and Benoit 2001). In addition to being an active port receiving many shipments of steel, lumber, oil, salt and sand; on the east side of the Harbor is a large, oil burning, electrical power plant, and on the west side is a sewage treatment plant that empties directly into the harbor (Spiegel 2006). The navigational channel is periodically dredged at ca. 15 year intervals to maintain a depth of approximately 10 m, but water depths elsewhere in the harbor are typically 1–7 m (Rozan and Benoit 2001). Most of the horseshoe crab spawning activity within New Haven Harbor occurs at Sandy Point, a long sand spit in West Haven, Connecticut that juts out into the middle of the Harbor (Beekey et al. 2013). Spawning takes place intermittently and at lower densities within the inner harbor in patches of sand that occur within broader areas of rubble fill and salt marsh (Beekey and Mattei 2008; Botton et al. 2009).

31.4 Opportunities for Citizen Science and Research in Urban Estuaries

The study of horseshoe crabs in urban estuaries provides excellent opportunities for public education and engagement with the local marine environment. The opportunity for ecological education of the public is one of numerous ecosystem services that urban estuaries provide (Haase et al. 2014). For example, horseshoe crab and shorebird viewing is a popular guided activity at the Jamaica Bay Wildlife Refuge, part of the Gateway National Recreation Area (NRA; Riepe 2001). At Plumb Beach, Brooklyn, another unit of Gateway NRA, faculty and students from Kingsborough Community College (KCC) and Fordham University partner with dozens of volunteers from the New York City Audubon Society in the annual high tide census of spawning horseshoe crabs (Colón and Rowden 2014). This is part of a larger survey effort in New York State designed to provide simultaneous coverage of spawning activity on a total of 12 evening high tides bracketing the new and full moons in May and June (Sclafani et al. 2009). Personnel first receive training from an experienced marine educator on how to conduct the survey; this is held in conjunction with the annual Eco-Festival at KCC, which also features lectures and exhibits about the local marine environment. Hands-on training continues in the field, where volunteers are shown how to distinguish sexes, tag animals, etc. Some students and volunteers participate in other aspects of the project, including core sampling to determine egg densities, measuring and determining carapace condition of adult crabs, and surveying the intertidal sand flats for the presence of juvenile crabs. This citizen science project has enormous value to the students and volunteers, many of which have little previous awareness of the ecological and biomedical importance of horseshoe crabs and are often unaware of the rich diversity of flora and fauna in their local marine habitats (Colón and Rowden 2014).

In 2014, the horseshoe crab research was used as the basis of a pilot program at Kingsborough Community College to add Citizen Science to the spectrum of Civic Engagement opportunities for students. Students who participated in the training and surveys were awarded credit towards their Civic Engagement graduation requirement. Students who participate in the summer research are funded through several grants including Bridges to the Baccalaureate through the National Institutes of Health (NIH) and C-STEP (Collegiate Science and Technology and Entry Program). These opportunities represent an entry point into scientific research and environmental activism for many students who have never explored the outdoors and were unaware of many local and global biodiversity and conservation issues. Raised either in an urban landscape where parks are places to avoid, or arriving from overseas and unaware of the natural landscape of New York Harbor, many Kingsborough students who participate in this research are deeply impacted by their first visit to an urban estuary and their first encounter with a live horseshoe crab.

To understand the horseshoe crab population dynamics within a single urban estuary like New Haven Harbor (NHH), faculty and students at Sacred Heart University (SHU) attempted to recruit people who frequent the beach to report basic information on spawning horseshoe crabs. From 1998 to 2000 the majority of people encountered on the beach were either repulsed by the sight of horseshoe crabs or were afraid of them because their telson looked like a stinger and their claws looked dangerous. However, to answer very basic questions about how far horseshoe crabs travel during their adult life span and if spawning adults tagged in NHH come back regularly to the same beach, it would be helpful if people who visit the beach frequently during the spawning season have a way to report their observations. In fact, with the millions of people who visit Long Island Sound annually, volunteers could be recruited from all around the Sound. It was not known at the start of the study if horseshoe crabs could cross the Sound on a regular basis or if they stayed within a specific estuary on the Connecticut coast. Evidence from studies in deep embayments in New England revealed that animals rarely leave (James-Pirri 2010). Yet other studies have evidence of horseshoe crabs traveling quite broadly over their 18–20 year life span (Swan 2005). So what would be the pattern in a large urban estuary?

In order to recruit volunteers to help, first an education program was needed so people would learn that horseshoe crabs are benign and are beneficial to humans and to the estuary they inhabit. Letters and emails were sent to local non-profit environmental organizations asking if they wanted to join a newly established conservation program called Project *Limulus* even though at the time it consisted of one professor and two undergraduate research assistants. Faculty and undergraduate students offered free lectures and beach walks/talks to their members. The staff members at the Connecticut Audubon Society, The Maritime Aquarium and The Nature Conservancy were trained to tag, record data and lead their own groups of volunteers out to local beaches during the spawning season. It was discovered that members of conservation organizations wanted to donate their time and be active participants in conservation activities rather than always be asked to donate money. After several years, Project *Limulus* had hundreds of volunteers (Mattei and Beekey

2008). The research and outreach programs were supported by Connecticut Sea Grant, Disney Worldwide Conservation Fund, the National Fish & Wildlife Foundation, the College of Arts & Sciences, Undergraduate Research Initiative at SHU and other local granting agencies. The outreach program was expanded to include local schools and teachers modifying the program to include children from pre-K to high school (Figs. 31.2 and 31.3). This also involved training students who were interested in a career in education. From 2007 to 2014 Beekey and Mattei and other Project *Limulus* staff delivered over 300 lectures, dozens of newspaper stories, three different spots on National Public Radio and on several occasions, local television news stories and the Aqua Kids TV show in 2009 and 2014. In 2013:

- Fifteen Project *Limulus* information sessions ran that targeted the general public, and 13 outreach programs were offered through the context of various non-profit organizations (see Table 31.1). Over 750 adults and 525 children participated in these outreach events.
- Project *Limulus* staff traveled to 15 schools ranging from 3rd to 12th grade (See Table 31.2). A total of 1,062 students participated in these outreach events along with 85 teachers and an additional 197 adults (parents of students who participated in the school field trips or in-school presentations).
- Outreach events were conducted for some summer regional enrichment programs targeting underprivileged children for a total of 160 students, 19 adults, and 21 teachers including 48 students involved with the Horizons National Youth Program run through Sacred Heart University (http://www.sacredheart.edu/academics/universitycollegepart-timenon-creditprograms/horizonsnationaly-

Fig. 31.2 Project *Limulus* Outreach Coordinator, Adam Rudman, with three undergraduate Biology students (Fordham and Sacred Heart University) are teaching the 2nd Grade class of Unquowa School in Fairfield, Connecticut the economic and ecological value of horseshoe crabs in Long Island Sound (Photo by: T. Deer-Mirek)

Fig. 31.3 Pre-school children, like 4-year old Alice Young, learn early that horseshoe crabs are harmless through public education programs like Project *Limulus* (Photo by: T. Deer-Mirek)

Table 31.1 Project *Limulus* outreach events in 2013

Group name	No. of kids	No. of adults
Ash Creek Nature Center	15	30
Beardsley Zoo	27	30
Bruce Museum	103	213
Connecticut Audubon	16	35
Darien Nature Center	19	13
Denison Pequotsepos Nature Center	65	121
Menunkatuck Audubon	51	146
Mystic Aquarium	50	66
Nature Conservancy	25	45
Private Group	26	12
Sherwood Island Nature Center	10	2
SoundWaters	100	20
CT Surfriders	20	20
Total	527	753

outhprogram/), 32 students from the Yale Exploration program (http://explo.org/360/yale), and 80 students participating in the Inter-district Aquaculture Program run through the Center for Creative Youth (Fig. 31.4; http://www.crec.org/magnetschools/schools/ccy/).

- Egg hatching kits were distributed to 22 classrooms from seven different school districts with a combined total of 790 students ranging from K-12th grade. All of the kits were successfully returned and all of the hatched horseshoe crabs were released back into the water on the beach where they were originally collected from. Overall our participating teachers had a 60 % hatching success rate that is similar to what we observe in laboratory conditions.

Table 31.2 K-12 Project *Limulus* Educational Outreach 2013

School/group name	Town	State	No. of students	Grades	No. of adults	No. of teachers
Madison Public School District	Madison	CT	281w		85	5
City Hill Middle School	Naugatuck	CT	120	8th	5	5
Harborside Middle School	Milford	CT	192	6th	29	27
Hopkins School	New Haven	CT	8	11–12th	1	1
Metropolitan Business Center	New Haven	CT	13	9–12th	2	2
Naugatuck High School	Naugatuck	CT	22	11–12th	3	3
Our Lady of Assumption School	Fairfield	CT	145	K-8th	26	21
Rye Country Day School	Rye	NY	30	11–12th	2	1
Sayless School	Baltic	CT	25	8th	1	1
Shelton Intermediate	Shelton	CT			1	1
St. Luke's School	New Canaan	CT	44	5th	6	6
St. Thomas School	Stratford	CT	17	1st	8	1
Unquowa School	Fairfield	CT	40	2nd grade, PreK4	16	3
ACES	Hamden	CT	25	9–12th	2	2
John G. Prendergast School	Ansonia	CT	100	9–12th	10	6
Total			1,062		197	85

An overlooked advantage of working in urban estuaries is their accessibility to students and volunteers, compared with more remote locations such as Delaware Bay. Jamaica Bay and New Haven Harbor are within the reach of millions of people by public transportation. Moreover, locations such as Jamaica Bay and New Haven Harbor provide a mosaic of habitat types in close proximity to each other, enabling visitors and volunteers to easily contrast horseshoe crab activity on relatively "natural" beaches and highly degraded habitats with bulkheads, rubble fill, or other kinds of human alterations.

31.4.1 Examining Recruitment in Horseshoe Crab Populations Using Volunteer-Based Projects

As a specific example of the kind of useful data that can be collected by students and citizen scientists, we have measured and determined carapace condition of adult horseshoe crabs in Jamaica Bay and New Haven Harbor for several years as an indicator of the "health" of the population (Duffy et al. 2006; Shuster 2009).

Fig. 31.4 High school students from Bridgeport, Connecticut help undergraduate research assistants from Sacred Heart University tag and collect data on spawning horseshoe crabs such as size, sex, and condition (Photo by: A. Rudman)

Although there are no known methods for determining the chronological age of adult crabs, the assignment of a "relative" age can be done quite easily by examining the condition of the carapace. We have used a simple scoring procedure (after Brockmann 2002; Duffy et al. 2006; Shuster 2009), which can easily be demonstrated to volunteers in the field. A score of 1 is given for a "young" or newly molted animal, which has a lustrous shell with sharp spines, typically with few if any attached invertebrates, and hairs are present along the inner edge of the prosoma (Fig. 31.5a). A score of 2 is used for a shell in intermediate condition ("middle age"), one that has scratches and other signs of wear, with some blackened areas, often with some coverage by barnacles, mussels (*Mytilus*), slipper shells (*Crepidula*), bryozoans, and other invertebrates. A score of 3 is assigned to "old age" crabs that have a thin, pitted, and heavily blackened shell, often with partial to complete rotting of the lateral eyes (Fig. 31.5b, Duffy et al. 2006). A classic model of population growth that reflects an increasing or expanding population would include greater numbers of younger adults (i.e. Condition 1) entering the population than older or aging adults (i.e. Condition 2 and 3). Equal numbers of young, middle aged and older adults would indicate a stable population. The characteristic configuration for relative age classes of a population in decline has disproportionately greater numbers of older adults (e.g. Pew Research Center 2014).

Using groups of volunteers, we measured and assessed carapace condition for horseshoe crabs from both the Jamaica Bay and New Haven Harbor populations in 2012 and 2013. Using multiple teams of three (one person to gather the crabs, the second to measure and determine carapace condition, and the third to record data),

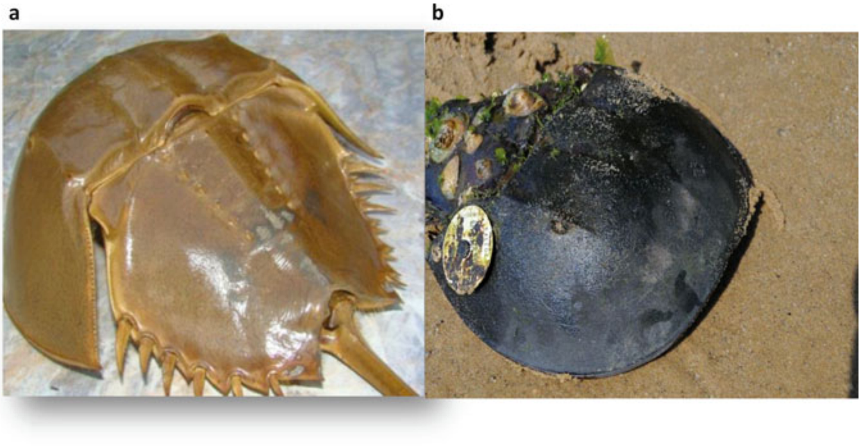
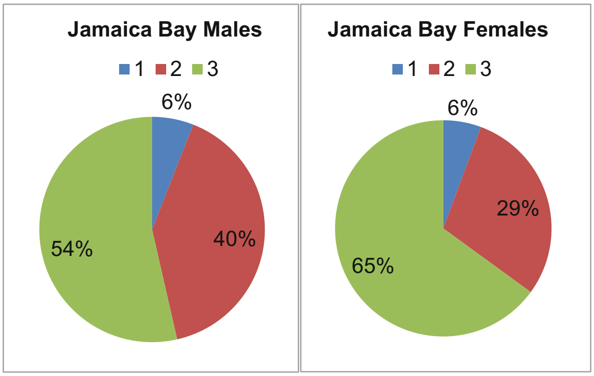


Fig. 31.5 Contrasting pictures of Condition 1 and 3 adult horseshoe crabs. (**a**) A newly molted Condition 1 adult female. Her shell is shiny, golden brown, with the hinged edge lined with small hairs. (**b**) An old, Condition 3 horseshoe crab with dull, black, pitted shell and damaged dark colored eyes. No hairs are present (Photo by: J. Mattei)

Fig. 31.6 Carapace condition of a sample of adult horseshoe crabs separated by sex from Jamaica Bay (N=84 females and 177 males) during the 2013 spawning season. Carapace condition was scored as (1) newly molted, (2) middle aged and (3) oldest (See text for description)



we can easily assess several hundred crabs on a single high tide, giving a robust sample for statistical analysis. Both Jamaica Bay and New Haven Harbor populations are dominated by condition 2 and 3 crabs (Figs. 31.6 and 31.7, respectively), suggesting that there has been little recent recruitment of new adults into the population. For JB in 2013, fewer than 6 % of the male and female crabs were judged to be new recruits (Condition 1, Fig. 31.6). This could have important demographic consequences, since alternative male mating tactics (attached vs. satellite) and the risk of beach stranding are known to be condition-dependent (Penn and Brockmann 1995; Duffy et al. 2006). With the help of volunteers in NHH, we were able to document variation in recruitment from year to year. The total spawning adults in 2012 that were recorded as condition 1 was 9 %, and in 2013 19 % were newly molted (Fig. 31.7). These percentages need to be followed for several more

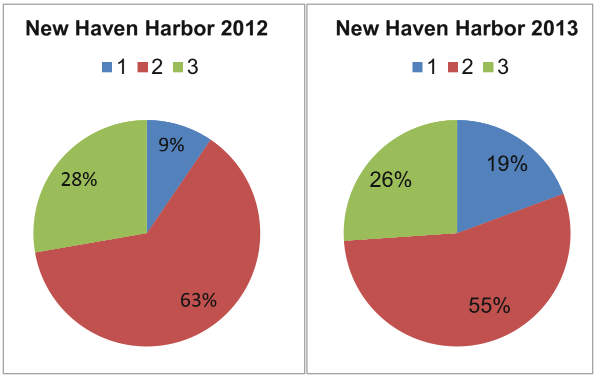


Fig. 31.7 Carapace condition of total adult spawning horseshoe crabs sampled from New Haven Harbor during the 2012 (N = 988) and 2013 (N = 993) spawning seasons. Carapace condition was scored as (1) newly molted, (2) middle aged and (3) oldest (see text for description)

years across more than one beach, but this preliminary data demonstrates that recruitment of young adults is low and that the population is declining. Data from our volunteers has redirected our efforts to investigate why more juvenile horseshoe crabs are not entering the spawning adult population.

Through our outreach programs that include training sessions, volunteers learn to tag horseshoe crabs as well as how to conduct a spawning census in order to estimate density of spawning females on a beach (tag data reported in Beekey and Mattei 2015). By modifying the protocol used in other states (James-Pirri et al. 2005; Smith and Michels 2006) volunteers count spawning adults on a pre-measured length of beach, walking at high tide covering the first 3 m into the water from the waterline. From these counts over a number of years we have discovered that the spawning density is well below estimates on Delaware Bay beaches in New Jersey and Delaware (0.03 +/− 0.04 females/m^2 in NHH and ~1.0 females/m^2 in DE) and that there is a lot of variation between counts, which was correlated with day vs. night, tidal height, moon phase, water temperature, wind speed, and from year to year (Mattei et al. 2010). While it is difficult to calculate actual population size in a large open body of water, with the help of volunteers one can obtain an estimate of spawning density on many different beaches and population trends over multiple years.

31.5 Summary and Conclusions

Horseshoe crab populations inhabiting urban estuaries are subjected to many different stressors, including pollution and shoreline development. Yet, these resilient animals are able to thrive in urban habitats such as New Haven Harbor and Jamaica Bay. Much of research on horseshoe crab ecology has come from studies in less developed embayments, such as Cape Cod and Delaware Bay. Mating behaviors, food web relationships, and many other aspects of ecology and behavior may prove to be significantly different in the urban settings. To begin to explore these differences in greater detail and to gain insights into how horseshoe crabs can survive in urban estuaries, we have found that help of citizen scientists drawn from nearby communities can be invaluable. In the long run, the conservation of horseshoe crabs depends on greater public awareness of the importance of these animals.

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