A Population Study of the Invasive Asian Shore Crab (*Hemigrapsus sanguineus*) Along the North Shore of Long Island Sound.

By

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Abstract

The Asian shore crab (*Hemigrapsus sanguineus*) has occupied the Atlantic Coast for the past thirty years (McDermott, 1991). In that time, the population of *H. sanguineus* has increased dramatically due to its ability to reproduce (McDermott, 1998), forage (Griffen et al., 2012) and out compete (Payne and Kraemer, 2013; MacDonald et al., 2007) other native species, becoming the most common shore crab along the beaches and shorelines. Invertebrate populations that have declined since the arrival of the Asian shore crab include the invasive European green crab, Atlantic blue crab, blue mussels and common periwinkles (Kraemer et al. 2007; Gilman and Grace, 2009). Although the Asian shore crab has been studied in Long Island Sound since its arrival, few studies have focused specifically on its effects to shoreline biodiversity. Results of this study showed that in the early fall of 2017, the Asian shore crab was the most abundant crab species at three locations along northern Long Island Sound; Edith G. Read Wildlife Sanctuary Rye, NY, Outer Island Branford, CT, and Stonington Point Stonington, CT. The abundance of shore crabs was highest at the Edith G. Read Wildlife Sanctuary Rye, NY in both August and September with the highest densities recorded in the upper intertidal zone at 26.2 crabs/m^2 and 32.4 crabs/m^2, respectively. The lowest crab densities were measured at Stonington Point with 2.4 crabs/m^2 and 2.9 crabs/m^2 for August and September, respectively. Large and medium sized crabs dominated the lower tidal zones, with few large crabs present in the upper intertidal zones. Surprisingly, the male to female shore crab ratios of 19:1 and 12:1 at these locations were much higher than those recorded in other regional studies. A comparison of crab densities over time regionally, and at Outer Island specifically, show that crab densities in intertidal areas have stabilized.

Chapter 1.
Introduction

The invasive species, *H. sanguineus* made its first appearance in 1987 at Cape May County, New Jersey (McDermott, 1991). Since then, the Asian shore crab population has increased and stretches as far north as Maine and all the way down to North Carolina (Benoit et al., 2005; McDermott, 1991; Kraemer et al., 2007; Griffen et al., 2012; Jouett and Child, 2014). With a population explosion of this magnitude, it was inevitable that negative impacts would be observed along local ecosystems. The preferred habitat of *H. sanguineus* are rocky tidal shores (Gilman and Grace, 2009; Jouett and Child, 2014; Westgate, 2011; McDermott, 1991; Kraemer et al., 2007), but the invasive crab has also been found in salt marshes (Brousseau et al., 2003). The Asian shore crab has an omnivorous diet, including cannibalism (Brousseau et al., 2014; Griffen et al. 2012; Roudez et al. 2007) making many species viable prey. What makes the Asian shore crab so successful as an invasive is their ability to produce numerous broods per year (McDermott, 1998a; Kraemer et al., 2007), aggression, and claw strength (Payne and Kraemer, 2013; DeGraaf and Tyrrell, 2004).

The northern Atlantic coast is optimal habitat for *H. sanguineus*. The Asian shore crab prefers rocky tidal shores which provide adequate protection from predators. Structural habitat complexity contributes to the success of the Asian shore crab in a given area (Jouett and Child, 2014; Lohrer et al., 2000; Child and Jouett, 2015). Adult shore crabs benefit in areas with larger rocks and boulders allowing mobility to forage while increasing abundance and density (Griffen et al., 2012; Griffen and Byers, 2009). It has been documented in several studies that shore crab density is correlated with the percent of rock cover along the tidal zone (Casanova, 1998; Jouett and Child, 2014). The greater the rock cover, the higher density of shore crabs likely to be found. Similarly, the larger the rock size in a suitable area, the larger quantity of shore crabs likely to be found taking shelter under that rock. Next to rock cover, tidal height is also important determining in Asian shore crab abundance (Silva et al., 2010). The Asian shore crab is most active during high tide because that is when they will most likely forage for food such as vegetation, clams, oysters, or other shore crabs (Griffen et al., 2015; Griffen et al., 2012). Another reason why shore crabs prefer rocky tidal habitats is the variety and availability of food in the intertidal zones (Bourdeau and O'Connor, 2003; Griffen et al., 2012, Silva et al., 2010). In contrast, *H. sanguineus* is inactive during low tide, especially during the daylight hours (Epifanio, 2013). For this reason, shore crabs are easily sampled during low tides as they are resting under rocks.

Currently, Asian shore crabs are the most common crab species found along the northern east coast of the United States. Structural habitat complexity, tidal height and multiple food sources contribute to the population growth of the Asian shore crab in rocky tidal zones. Another reason for their success has to do with warm temperatures (Stephenson et al., 2009; Epifanio, 2013). Shore crabs are very tolerant of temperature changes which give them an advantage over native species along the rocky tidal shores. However, this is not true when the shore crabs are in their larval stages. *H. sanguineus* can reproduce four to five times in one breeding season (Epifanio, 2013; McDermott, 1998a; Westgate, 2011). Other crabs in the area such as the European Green crab and Atlantic blue crab only reproduce once a season. Asian shore crabs can produce up to 200,000 larval between April and October of a given year (McDermott, 1991, McDermott, 1998a). The time of year is important to note for the breeding season of shore crabs because this may be the reason why it has failed to completely take over rocky tidal shores over the coast of Maine. Warmer water temperature plays a role on where a female Asian shore crab can reproduce successfully. In studies conducted in Maine, they have shown that a higher percentage of *H. sanguineus* larval in colder temperatures fail to reach the juvenile stage (Stephenson et al., 2009). The colder temperatures also slowed down the larval developmental stages. The longer *H. sanguineus* remains in the larval stage, the longer they are vulnerable to predation. However, with climate change occurring, water temperatures are warming and it may be just a matter of time before the shore crab becomes the most abundant shore crab along the entire coast of Maine.

The Asian shore crab introduction has led to other ecological and local ecosystem problems (Bloch et al., 2015; Kraemer et al., 2007). With the shore crabs' ability to spread quickly in a preferred environment, it out competes local species for shelter and food (Griffen, 2011; Westgate, 2011). Populations of several common intertidal species (including non-native) have had population declines across the board (Kraemer et al., 2007; Cockrell et al. 2015; Westgate, 2011). Affected species include the Atlantic blue crab (*Callinectes sapidus*), blue mussel (*Mytilus edulis*), European green crab (*Carcinus maenas*), and mud crab (*Eurypanopeus depressus)* Blue mussel populations have been declining steadily for two decades and the Asian shore crab has played a part in this outcome (Auker et al., 2014; Bourdeau and O'Connor, 2003; Brousseau and Goldberg, 2007; Brousseau et al., 2014; Lohrer and Whitlatch, 2002). The Atlantic blue crab, similiar to the blue mussel, has had severe population declines due to its inability to compete with the Asian shore crab in their juvenile stages (Roudez et al., 2007; MacDonald et al., 2007). The European green crab, another invasive, has also been impacted by the arrival of the Asian shore crab. The green crab was once the most common crab found along Long Island Sound, but their inability to reproduce and successfully fight for food and shelter has left them displaced (Audet, et al., 2003; Casanova, 1998; Griffen, 2011; Griffen et al., 2008).

Chapter 2.

Study Approach

The Asian shore crab has been shown to influence intertidal species composition. With populations of *C. maenas*, *C. sapidus*, *M. edulis*, and *E. depressus* declining, it is likely *H. sanguineus* has played a role in their respective population declines. It is therefore important to examine how Connecticut's shoreline intertidal ecosystems have been affected by *H. sanguineus*. Kraemer et al. (2007) examined the long-term displacement of established rocky tidal shore species by *H. sanguineus*. Their findings were astounding, within 8 years the Asian shore crab was the only crab species found at the Edith G. Read Wildlife Sanctuary, Rye, NY. Similar studies have been conducted in Connecticut at locations including Outer Island in Branford and Hammonassett State Park in Madison, Connecticut. Casanova (1998) focused on examining the abundance of the Asian shore crabs and the European green crabs in the intertidal zone at Outer Island. Casanovas' results showed that the Asian shore crab was the most abundant shore crab with the green crab rarely found throughout the study. A similar study conducted at Stonington, CT and along the Rhode Island shoreline focused on shore crabs with missing limbs and appendages and possible effects it had on their populations and food consumption (Davis, et al., 2005). The authors results suggested possible impacts on population growth but that the Asian shore crab would continue to thrive even with some missing appendages.

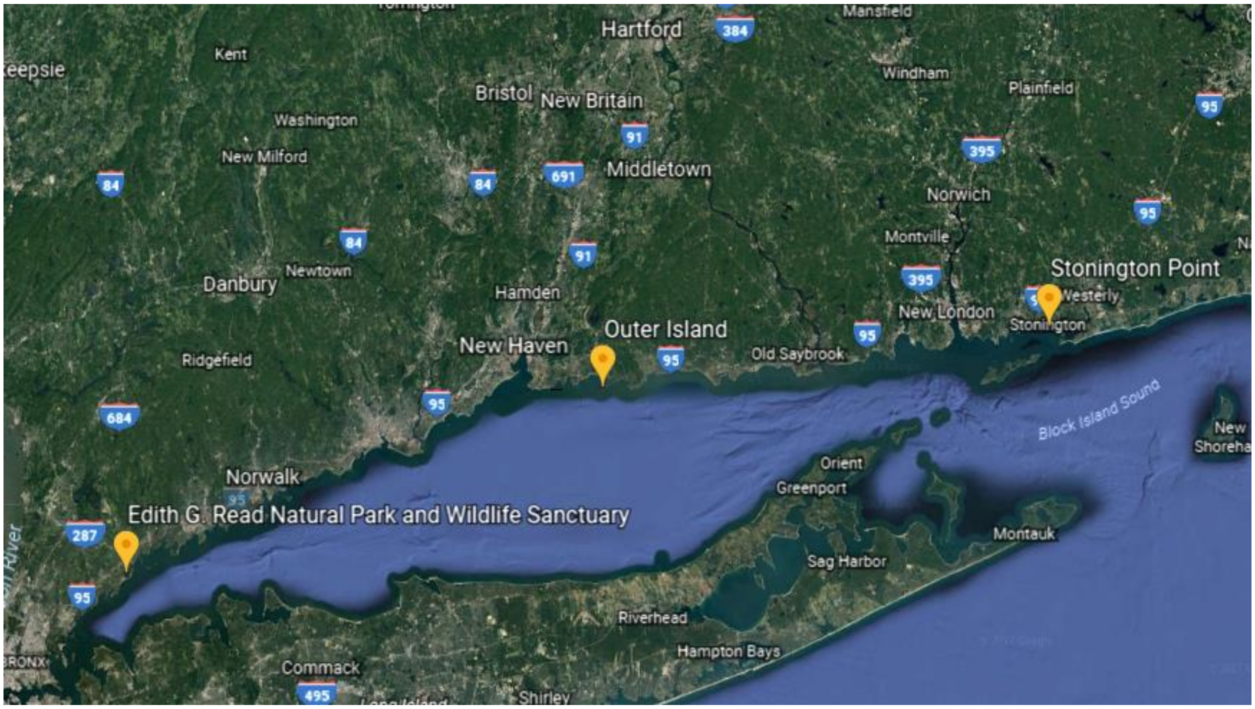
Three locations along northern Long Island Sound with intertidal habitat preferable to shore crabs were chosen for this study. The three sites chosen for sampling were Edith G. Read Wildlife Sanctuary in Rye, New York, Outer Island in Branford, Connecticut and Stonington Point in Stonington, Connecticut. These sites are rocky intertidal zones composed of varying sizes of cobble and rocks and are located eastern, central, and western Long Island Sound. Crab population counts were conducted in the intertidal areas at these three locations in August and

September of 2017. Previous studies have conducted shore crab counts at each of these locations on one or more occasions. The Edith G. Read Wildlife Sanctuary has eight years of published data on shore crab populations from 1998-2005 (Kraemer et al., 2007). Outer Island had previous *H. sanguineus* data from a study conducted by Tara Cassanova in 1998 and yearly crab counts by Virginia Baltay (1999-2015; unpublished data). Stonington Point Asian shore crab data was obtained from a single study (Davis et al., 2005). Results of this proposed shore crab population study were compared to those previous studies to determine long-term trends in shore crab populations. This study was also designed to answer the following questions: Does shore crab abundance vary among the sites in this study?; and does shore crab abundance vary within a given site due to variations with intertidal elevation? I hypothesized that results from this study would indicate a preference for Asian shore crabs along the lower intertidal zones.

2.1. Material and Methods

The population of *H. sanguineus* was quantified on the northern shores of Long Island Sound. For this study, three sampling sites that had previous population data documented on the Asian shore crab were selected; Rye, New York (40.58’1”N, 73.39’48”W), Outer Island of the Thimble Islands in Branford, Connecticut (41.24’21”N, 72.76’05”W), and Stonington Point, Stonington, Connecticut (41.19’79”N, 71.54’57) (Figure 1). All three locations are rocky intertidal shores with cobbles and rocks, yet each site was different. At the Rye site in New York, the tidal range was between 8-9 feet during spring low tide. Given the tidal range at Rye, three tidal elevation zones were established. The cobble and rock diameters at this site varied from a few inches to several feet along the lower intertidal zone (Figure 2a & b). The sediment was muddy in the lower intertidal zone as compared to the middle and higher intertidal zones. Outer Island of the Thimble Islands is located off the coast of Branford, Connecticut. The Outer

Figure 1. The three sampling sites along northern Long Island Sound. Sample locations are marked with a yellow pointer and labeled as (west to east) Edith G. Read Wildlife Sanctuary, Rye New York, Outer Island in Branford, CT, and Stonington Point in Stonington, CT.

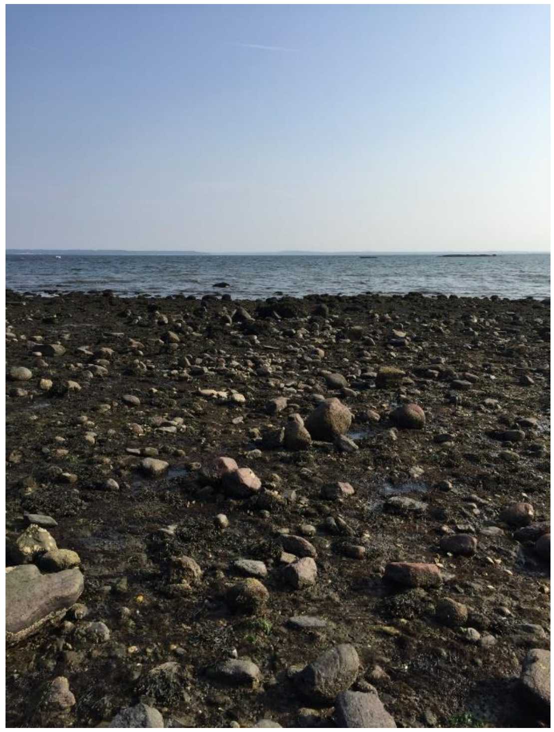


Island intertidal zone was composed of varied cobble and rock sizes. However, there were fewer large rocks compared to Rye (Figure 3). The underlying sediment at Outer Island was coarser in texture compared to the other two sites. Tidal range at this location reached between 6-7 feet during spring tide. Due to a lower tidal range, two intertidal sampling zones were established 4.5 feet above MLW. Stonington Point was the smallest of the three sites in total area and had a comparatively lower tidal elevation of just over three feet (Figure 4). The shoreline at this location was composed of only large rocks and very few cobbles. Due to the low tidal range, only one intertidal sampling zone was established. During each sampling event; salinity, dissolved oxygen, temperature, and intertidal elevation (results not shown) were documented. The tidal elevation at each site was referenced to mean low water (MLW) based on published data from the Tides and Currents section of NOAA website (https://tidesandcurrents.noaa.gov).

2.2. Sampling Methods

Each sampling site had different intertidal sampling area sizes due to differences in their respective tidal ranges. The width of sampling areas was established with measuring tape. Rye, New York had the highest tidal range between 8.7-8.9 ft allowing the sampling plot to be forty meters wide from -0.1m MLW to +2.2m MLW. Fifteen quadrat samples were collected from within that region. Within each area: five samples were taken within each of 3 regions: -0.1m – +0.7m, +0.7m – +1.5m, and +1.5m – +2.2m. At Outer Island, the intertidal area sampled was 25 meters wide due to a comparatively lower tidal range from -0.1m MLW to +1.5m MLW. Within the region, sixteen samples were obtained: eight samples from -0.1m – +0.7m above MLW, and another eight from +0.7m – +1.5m above MLW. Only two zones were possible because the tidal elevation was only between 6.3 and 7 ft. However, in the September data collection, only five samples were taken in the +0.7m- -0.1m MLW due to time constraints. The Stonington Point

Figure 2. Spring low tide at Edith G. Read Wildlife Sanctuary, Rye, New York. Photo (a) is of the low intertidal zone at -0.1m below MLW. Photo (b) is at 1.5m above MLW. The site consists of cobbles and boulders overlying a muddy gravel.



(a)

(b)

Figure 3. Neap tide at 0.1m above MLW on Outer Island, Branford, Connecticut. This site contains cobbles and boulders with a coarse sand underneath.

Figure 4. Neap tide at -0.05m below MLW on Stonington Point, Stonington, Connecticut. This site consists of cobbles and boulders with fine sand underneath.

intertidal area was 30 meters wide, but only had a tidal range of about 3 ft allowing for only one sampling zone -0.1m MLW to +0.7m MLW. All fifteen samples were collected from within this zone.

Sampling at all sites was accomplished using a 1m x 1m quadrat (Figure 5). Within each grid, rocks were picked up one at a time and returned to their original position. All rocks were moved unless the weight of the rock was too heavy to be moved by hand. Captured crabs were placed into a bucket from their respective $1m^2$ quadrat. Next, the Asian shore crabs' sex was verified, and carapace width measured using a Neiko digital caliper. When all quadrat data was recorded, crabs were released within their original intertidal areas. Crabs were not released until after all data had been collected to avoid possible recounting of individual crabs.

Figure 5. A 1m x 1m quadrat sample plot taken at Outer Island in Branford, CT.

Chapter 3.

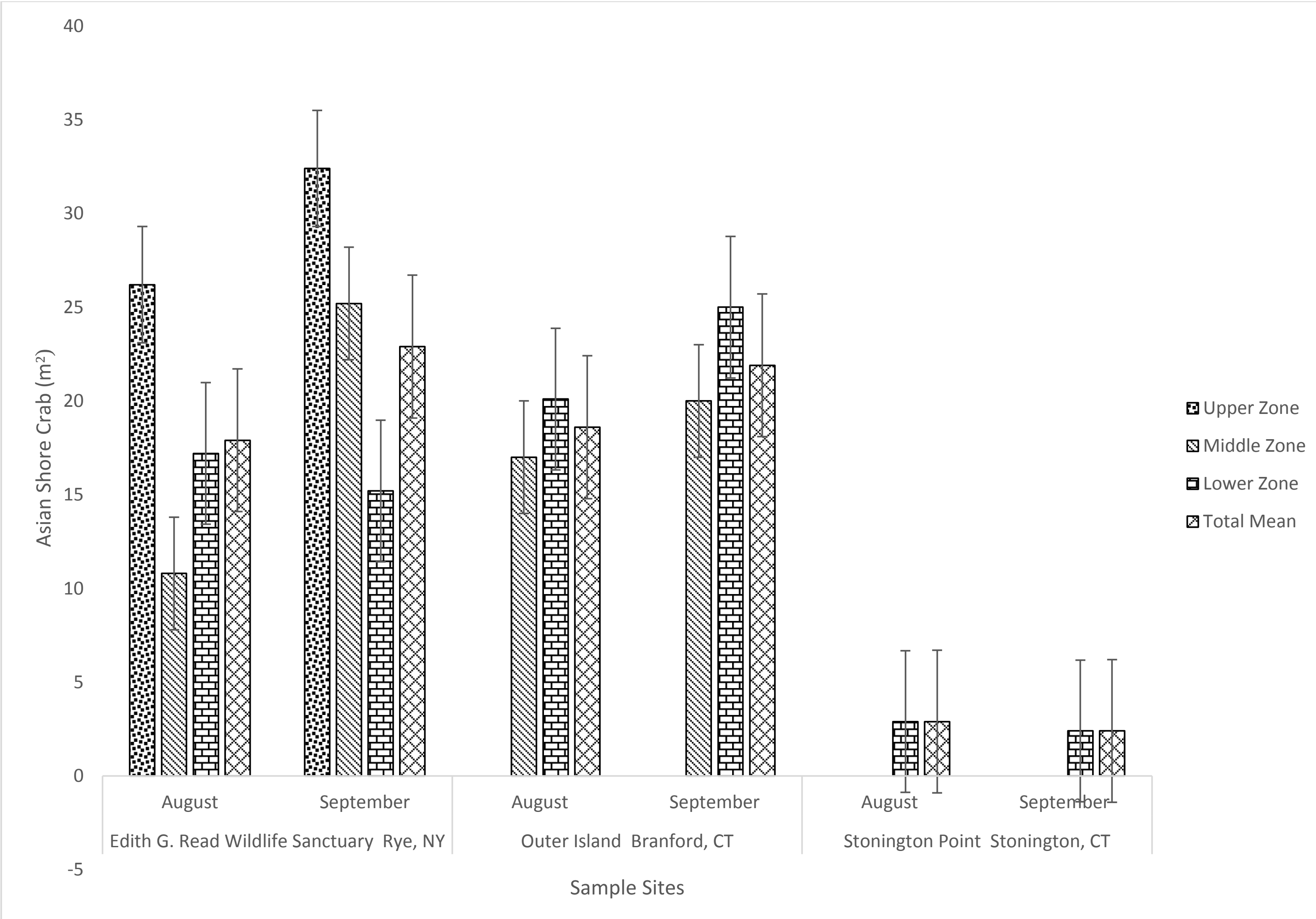
Results

3.1. Shore Crab Abundance

Except for a European green crab found at the Edith G. Read Wildlife Sanctuary in September and another at Outer Island in August, the Asian shore crab was the only crab species captured at all three sites throughout the study. The crabs collected at the Edith G. Read Wildlife Sanctuary and Outer Island locations were similar in abundance, whereas Stonington Point crab abundances were lower. Crab densities at the Edith G. Read Wildlife Sanctuary and Outer Island in September (22.9 and 21.9 crabs/m², respectively) were higher compared to August (17.9 and 18.6 crabs/m², respectively). Stonington Point crab densities for August and September were 2.9 and 2.4 crabs/m², respectively (Figure 6). The densities at Stonington Point were far lower than the other two sites.

Edith G. Read Wildlife Sanctuary and Outer Island crab densities increased in all intertidal zones from August to September. The density of the upper tidal zone (2.2-1.5 MLW) at the Rye site was 26.2 crabs/m² in August and increased to 32.4 crabs/m² in September. Lower tidal zone crab densities (0.7- -0.1 MLW) for August and September were lower with 17.2 crabs/m² and 22.9 crabs/m², respectively. Crab densities of the lower and mid-intertidal zone at Outer Island increased from August to September. The mid and lower intertidal zone crab densities in August were 17 crabs/m² and 20.1 crabs/m², respectively as compared to 20 crabs/m² and 25 crabs/m², respectively in September. Different from the Edith G. Read Wildlife Sanctuary, the crab densities were higher in the lower tidal zone at Outer Island (Figure 6). Stonington Point crab densities in August and September were comparable at 2-3 crabs/m². In

Figure 6. Asian shore crab densities in the intertidal zones (Upper = 2.2-1.5, Middle = 1.5-0.7, Lower = 0.7- -0.1MLW) at the three sampling areas in Long Island Sound.



contrast to the other sites, crab densities declined from August to September at Stonington Point (Figure 6).

3.2. Shore Crab Size

The Asian shore crab carapace width (CW) measurements at all sites varied (Figure 7). The three size categories of CW were; small= ≤14 mm, medium = 14-24 mm, and large = ≥24 mm. Average CW of *H. sanguineus* was smallest at Outer Island on both sample dates (10.3 mm in August and 9.62 mm in September) (Figure 7). Average CW was highest at Edith G. Read in August at 14.07 mm and Stonington Point in September at 12.43 mm (Figure 7). The Edith G. Read Wildlife Sanctuary upper intertidal zone had smaller CW averages of 11.87 mm and 9.53 mm. The Edith G. Read Wildlife Sanctuary consisted of three tidal zones, but almost no medium and large size crabs were observed in the upper intertidal zone (Figure 7). The lower intertidal zones at all three sites is where average CW was highest and ranged from 16.91 mm at the Edith G. Read Wildlife Sanctuary to 10.84 mm at Outer Island in September (Figure 7).

The density of smaller sized shore crabs at the Rye site and Outer Island were significantly larger when compared to medium and larger sized crabs in the mid and lower tidal zones (Figure 8). Small sized males at the Edith G. Read Wildlife Sanctuary dominated the population at 94% and 95% respectively, in both months (Figure 8). The percentage of male shore crabs collected decreased (57%, 75%) for medium sized crabs (Figure 8). All large crabs collected at all sites were male. At Outer Island, the overwhelming majority of small shore crabs were males in August and September (98% and 92%, respectively) (Figure 8). Medium sized crabs were also predominantly male (71% and 65%, respectively) in both months. There were only three large shore crabs in both Outer Island counts. One large crab was captured in August (100%) and the other two in September (50%, 50%). The highest percentage of shore crabs found in the upper

Figure 7. Asian shore crab sizes (mm) in the intertidal zones.

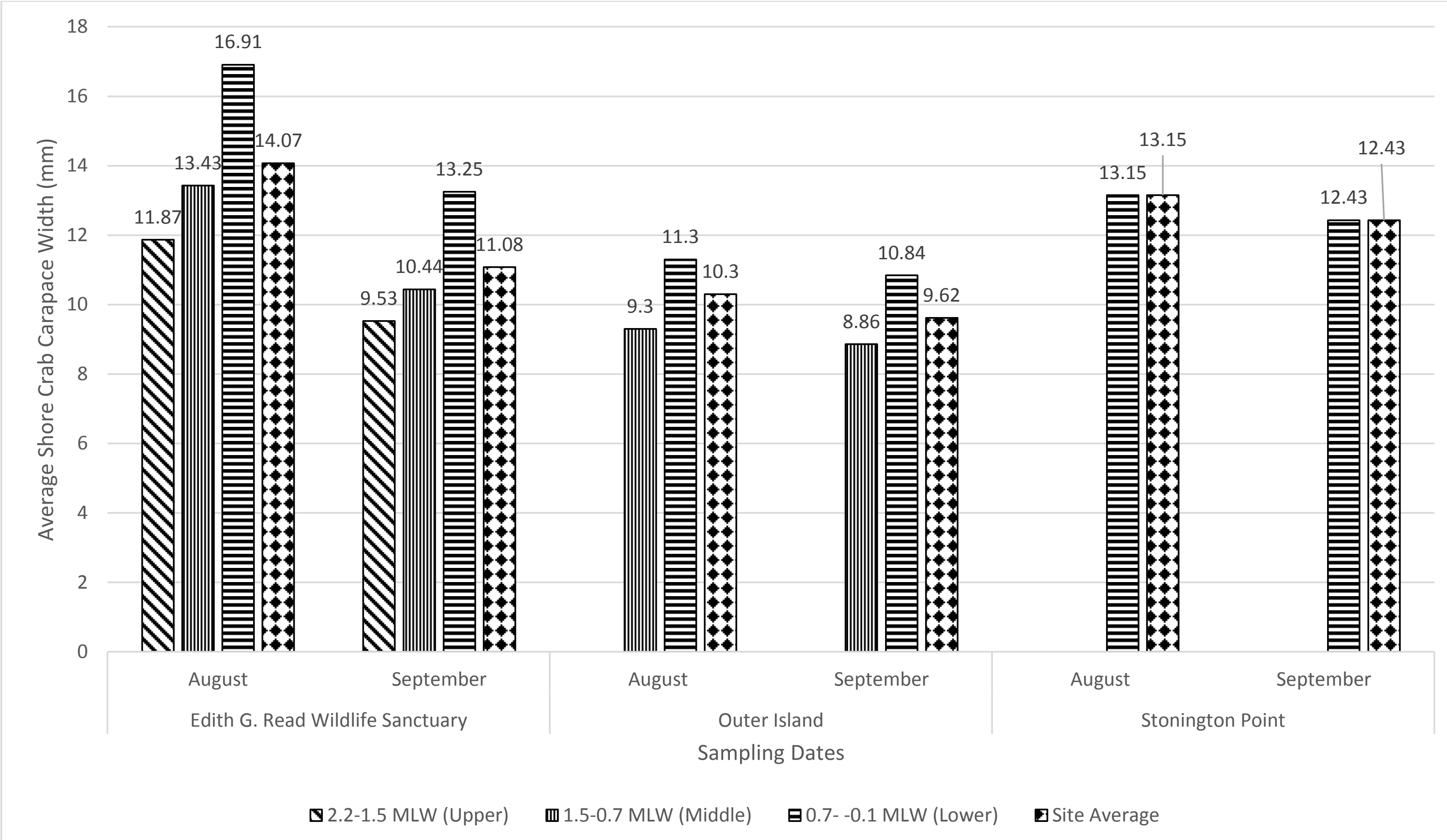
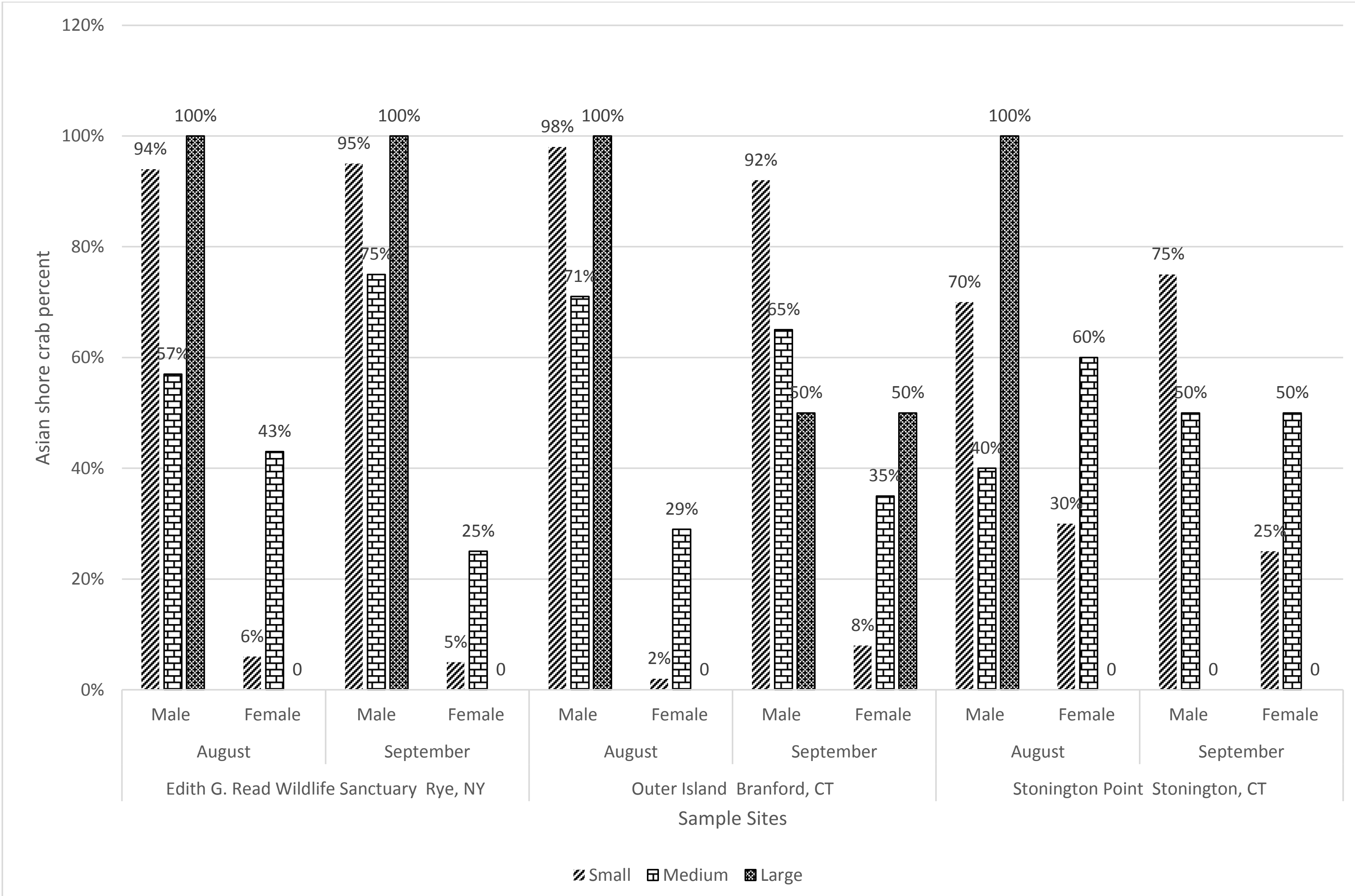


Figure 8. The percent of Asian shore crab size versus gender at all three sampling sites. Small (≤14mm), Medium (14-24mm), and Large (≥24mm).



tidal zone at any site was at Outer Island with 88% in August and 91% in September (Figure 8). Stonington Point had similar size percentages in both August and September counts for small males at (70% and 75%), and medium sized male crabs (40% and 50%) (Figure 8).

3.3. Shore crab gender

The gender and sizes of the Asian shore crab were not equally distributed at all sites (Table 1). At all sites, male and females CW sizes were separated into three categories; small (less than 14 mm), medium (14-24 mm), and large (more than 24 mm) (Table 1). Male dominance was most pronounced in the upper intertidal zones at Edith G. Read Wildlife Sanctuary and Outer Island.

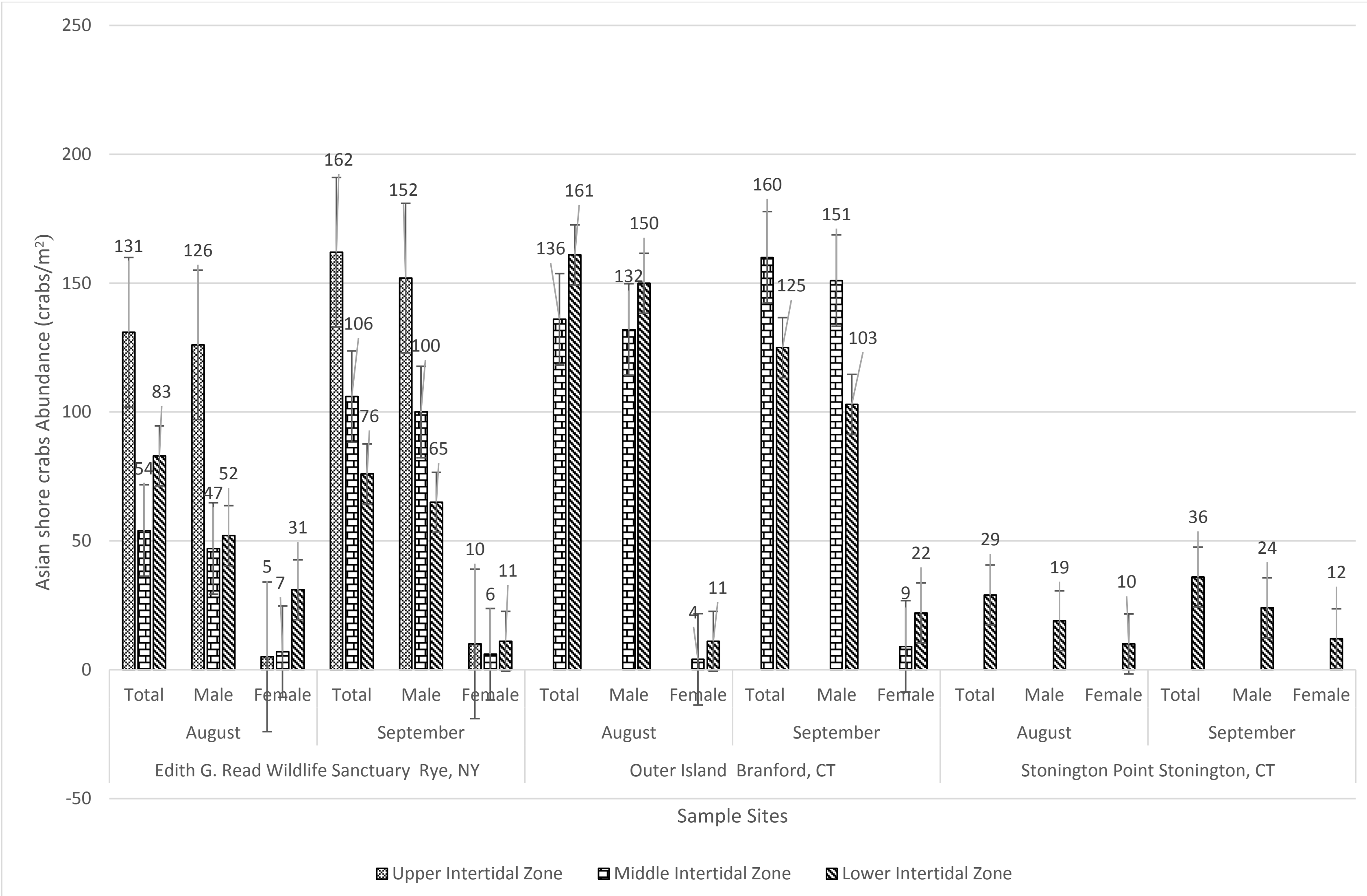
At the Edith G. Read Wildlife Sanctuary in August, the ratio of male to female was 19:1 in the upper intertidal zone (Figure 9). At Rye and Outer Island, the discrepancy between males and females was similarly high in both August and September (Table 1). In September at Outer Island, the middle intertidal zone also had a strong male dominance ratio 12:1. Stonington Point in both August and September had a more balanced male to female ratio of 2:1 on each sampling date. Females were most abundant at the Rye site followed by Outer Island, and then Stonington.

At Edith G. Read Wildlife Sanctuary and Outer Island, small Asian shore crabs males (CW≤14 mm) outnumbered females by significant margins (Table 1). Larger crabs (CW≥24 mm) were primarily found at the Rye site, 19 in August and 3 for September. Larger shore crabs were scarce at both Outer Island and Stonington Point with only four large crabs captured on both sampling dates. Large shore crabs collected were all male except for one female collected at Outer Island in September. Gender ratios of crabs at 1:1 were observed in medium sized shore

Table 1. Asian shore crab Male:Female gender ratio and totals by carapace width at each sample site.

Asian Shore Crab Carapace Width and Sex																		
Location	Edith G. Read Wildlife Sanctuary Rye, NY						Outer Island Branford, CT						Stonington Point Stonington, CT					
Month	August			September			August			September			August			September		
Gender	M	F	M:F	M	F	M:F	M	F	M:F	M	F	M:F	M	F	M:F	M	F	M:F
Small (≤14mm)	158	11	14:1	271	13	21:1	257	5	51:1	238	22	11:1	16	7	2:1	18	6	3:1
Medium (14-24mm)	47	33	1.4:1	43	14	3:1	24	10	2.4:1	15	8	2:1	2	3	1:1.5	6	6	1:1
Large (≥24mm)	19	0	1:0	3	0	1:0	1	0	1:0	1	1	1:1	1	0	1:0	0	0	n/a
Monthly Total	268			344			297			285			29			36		
Total	612						582						65					

Figure 9. Asian shore crab abundance (crabs/m²) and gender within each intertidal zone at three sampling sites in northern Long Island Sound.



crabs (CW 14-24mm) at all sites (Table 1). At the Rye site, the gender ratio of medium sized shore crabs for August and September was 1.5:1 and 3:1. Similarly at Outer Island gender ratios for medium sized crabs in both months was about 2:1. The only instance the ratio of male to female shore crabs favored females was observed for medium size crabs of 1.5:1 at Stonington Point in August. One of the largest shore crabs found at any of the three sites was a male at Stonington in August where the CW measured 32.9mm. Stonington Point was the only location where gender ratios were close at 1:1. The ratio of males to females were 2:1 and 1:1 in August and September, respectively (Table1).

Chapter 4.

Discussion

4.1. Shore Crab Population Trends

Previous researchers have conducted continuous long-term studies comparing Asian shore crab densities at a single location (Table 2). Casanova (1998) and Baltay (2017) have sampled shore crab densities at Outer Island in the late summer and early fall from 1998-2017. Casanova and Baltay Asian shore crab densities were graphed to show trends in density over time. Results of this study on shore crab density at Outer Island are shown for comparison for 2017. Shore crab densities from my study are comparable to abundances determined by Baltay in recent years. During the period 1998-2017, Outer Island shore crab densities declined from a peak of (56-68 crabs/m^2) to more stable levels over the past decade (20-41 crabs/m^2) (Figure 10).

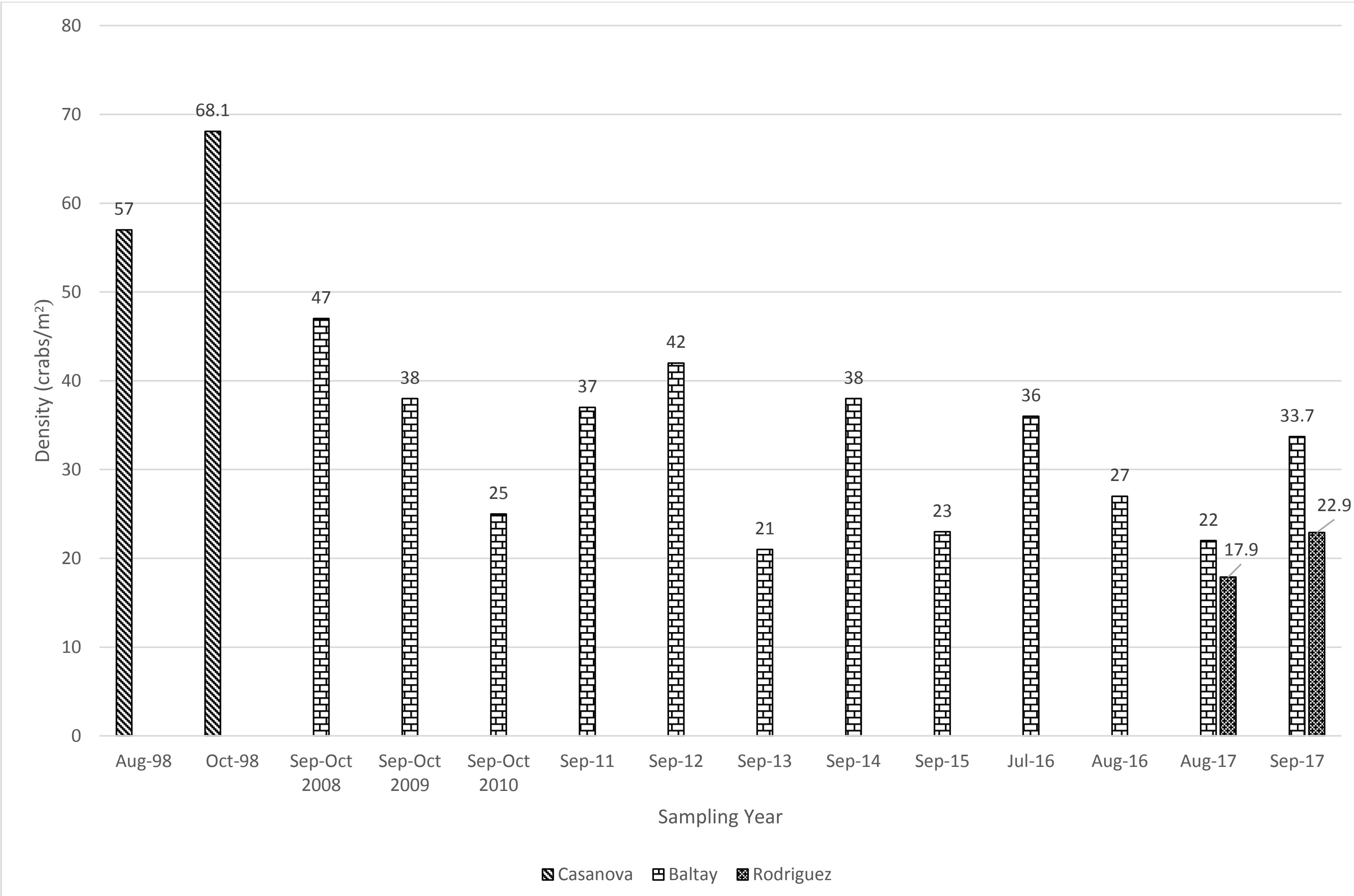
In another study conducted at Edith G. Read Wildlife Sanctuary (Kraemer et al., 2007), shore crab densities were examined throughout all seasons of the year with more emphasis in the June sampling. Abundances in early summer were some of the highest documented at just over 123 crabs/m^2 in 2001 and 2002, but even greater numbers were found in individual quadrats with a high density of 305 crabs/m^2 (Kraemer et al., 2007). Results from Rye in this study did not show comparable high crab densities. It is possible that the Asian shore crab population at Rye might have peaked in the early 2000s and stabilized in recent years which has been observed in other invasive species (Schab, 2013). The highest densities found in Kraemer's data (Table 2) were noted in the month of June in 2001 and 2002, afterwards densities began to decline steadily in each of the next three years.

At the Rye sampling site, the highest crab densities (crabs/m^2) in this study were found in the 2.2-1.5MLW region (Upper intertidal zone) which is consistent with other studies (Gilman

Table 2. Asian shore crab densities from previous studies around New England.

Author	Location	Year	Density (m^2)
Kraemer et al. (2008)	Edith G. Read Wildlife Sanctuary Rye, NY	1998 (June)	9.3
		1999	11.9
		2000	54.2
		2001	124.8
		2002	123.5
		2003	82.7
		2004	80.9
		2005	74.7
Bloch et al. (2015)	Town Neck Beach Sandwich, MA	2003 (September)	5.3
		2004	7
		2005	4.7
		2006	9.7
		2007	16.7
		2008	15.3
		2009	25.3
		2010	30
		2011	19.3
		2012	31
Casanova (1998)	Hammonassett State Park Hammonassett, CT	1998 (September)	71
		1998 (November)	67
Casanova (1998)	Outer Island Branford, CT	1998 (August)	57
		1998 (October)	68.1
Baltay (2017)	Outer Island Branford, CT	2008 (Sept-Oct)	47
		2009 (Sept-Oct)	38
		2010 (Sept-Oct)	25
		2011 September	37
		2012 September	42
		2013 September	21
		2014 September	38
		2015 September	23
		2016 (August)	36
		2016 (September)	27
		2017 (August)	22
		2017 (September)	33.7
Rodriguez (2017)	Edith G. Read Wildlife Sanctuary Rye, NY	2017 (August)	17.9
		2017 (September)	22.9
Rodriguez (2017)	Outer Island Branford, CT	2017 (August)	18.6
		2017 (September)	21.9
Rodriguez (2017)	Stonington Point Stonington, CT	2017 (August)	2.9
		2017 (September)	2.4

Figure 10. Asian shore crab densities (crabs/m²) at Outer Island from the mid 90s' to the fall of 2017.



and Grace, 2009). The 1.5-0.7MLW area (middle intertidal zone) was substantially different in August (10.8 crabs/m²) and September (25.2 crabs/m²). These differences could be due to habitat variation at different tidal elevations. In the middle intertidal zone some quadrat sampling was done in silty, muddy areas resulting in densities as low as three shore crabs per meter squared. Even though densities were highest in the upper MLW zone, many of the crabs were small, the larger crabs were typically found in the lower intertidal zones (1.5-0.7 and 0.7- -0.1MLW).

The lowest crab abundances were found at Stonington Point with 2.9 crabs/m² in August and 2.4 crabs/m² in September. The low abundance observed at this location may be due to characteristics of the intertidal habitat (Lohrer et al., 2000). Stonington Point has three factors affecting the intertidal area: wave energy, big rocks and boulders, and an overall smaller intertidal area compared to the Edith G. Read Wildlife Sanctuary and Outer Island. The wave energy at this site is very strong making shelter more difficult and unpredictable for shore crabs. The larger rock sizes at this location provide more than enough shelter from predators. However, feeding and movement along the large rocks during high tide becomes less optimal. With the site being small, it is hard for a population to thrive with less space, shelter, prey, and food sources in the area. Even with the low crab abundances observed at Stonington, some of the largest carapace widths were documented at this site. At Stonington, it seemed that the larger the boulder, the larger the crab observed which has been similarly seen in other studies focusing on rock size (Casanova, 1998; Lohrer et al., 2000; Jouett and Child, 2014).

4.2. Shore Crab Seasonal Population Trends

Previous studies have shown that the highest abundances of shore crab are found in the late summer and early fall (Kraemer et al., 2007; Bloch et al., 2015). The late fall and early winter months are when Asian shore crab populations drop drastically due to declining water temperatures. Most shore crabs in winter are most likely found in the low and mid intertidal zones. Crab size is similarly impacted throughout the intertidal zones in winter as bigger crabs move sub tidally to forage for food (Gilman and Grace, 2009; Kraemer et al., 2007).

Late summer and early fall shore crab abundances are higher because the breeding season for Asian shore crabs comes to an end in late October and November depending on water temperature (Epifanio, 2013; McDermott, 1998b). Asian shore crabs are highly tolerant of surrounding conditions such as temperature and salinity, but the larvae are vulernable (Rewitz et al., 2004; Schab, 2013). As larvae mature, survival then becomes more reliant on the habitat.

4.3. Structural Habitat Complexity

The results of previous studies have shown that structural habitat complexity greatly impacted Asian shore crab density and carapace width in rocky tidal shores (Child and Jouett, 2015; Lohrer et al., 2000). In this study, the sampling site at Rye, NY (Figure 2) was excellent habitat for a population of Asian shore crabs to thrive. At Edith G. Read Wildlife Sanctuary, waves are low energy having minimal impact on any organisms on the rocky tidal shore. The slope and rock placement are conducive for shore crab movement during high tide for foraging (Griffen et al., 2012; Silva et al, 2010). The forty-meter plot (Figure 2) was characterized by silty and muddy sediment and medium sized rocks. This combination makes for good habitat conditions for the Asian shore crabs during low tide and provides shelter from predation (Silva et al., 2017). There were also very large boulders in the 0.7- -0.1MLW lower tidal zone that provided shelter for many crabs. Casanovas (1998) showed a correlation between small and medium sized crabs with smaller rock sizes of about 80-100 mm, but no correlation with larger crabs and rock sizes. A better crab density and rock size correlation can be observed in Jouett and Child (2014). The crab densities in their study showed positive correlations with crabs and various rock cover.

Outer Island, Branford had the best structural habitat of any of the three sampling sites. Besides a few large rocks and boulders, it was mostly composed of equally sized rocks and sandy sediment (Figure 3). The abundance of rocks provided adequate protection from predators. The sediment and substrate are also ideal for the shore crab to move easily and burrow. The largest carapace widths were recorded in the 0.7- -0.1MLW tidal zone where the larger rock and boulders were found, similar to both the Edith G. Read Wildlife Sanctuary and Stonington Point.

Stonington, CT was a much different physical setting from the other sampling sites. Stonington Points' structural habitat was mostly comprised of large rocks and boulders (Figure 4) and had very limited small sized sediment as a substrate. This location is a comparatively high energy site in a narrow intertidal area which allowed for only one zone for sampling; 0.7- -0.1MLW. It was not surprising to find lower crab abundances at Stonington as the site is a less conducive environment for *H. sanguineus*. This narrow area had a sharper slope compared to Edith G. Read Wildlife Sanctuary and Outer Island, however slope is not as important to crab densities as is available shelter and structural complexity. It is the ability of shore crabs to find shelter, food and mobility that greatly impacts crab densities in intertidal zones (Epifanio, 2013; Lohrer et al., 2000). Actual rock sizes were not measured in this study, but an examination of Figures 2-4 shows noticeable differences in rock size at the three sampling sites. There was a strong similarity between Rye and Branford sites; the larger size boulders and rocks at the lower tidal zones produced most of the medium (14-24 mm) and large (>24 mm) sized crabs (Casanova, 1998; Jouett and Child, 2014; Lohrer et al., 2000).

4.4. Shore Crab Gender Ratios

The results of this study show a strong gender disparity at two of the three sites (Figure 7). At the Edith G. Read Wildlife Sanctuary in September, results showed a 12:1 ratio in favor of males. Similarly, Outer Islands' August data showed a 19:1 Male:Female ratio (Table 3). These Male:Female ratios are unusual but have been observed in other shore crab studies (Gothland et al., 2013; Abello et al., 1997; Rewitz et al., 2004), but not consistently. Gothland et al. (2013) collected Asian shore crabs in different areas off the eastern and southern coast of France resulting in gender ratios of 1:1, 2:1, and 3:1. However, one sample had an unusually high gender ratio of about 8:1 in Sennerville. The only reasoning given had to do with salinities being at low levels. Females Asian shore crabs need certain water temperatures and salinities to spawn broods (Epifanio, 2013; Rewitz et al., 2004). If the needs are not met, females will try to relocate to areas with adequate salinity conditions of at least 26ppt and temperatures of about 10 degrees Celsius (Rewitz et al., 2004). The salinities at Edith G. Read Wildlife Sanctuary for August and September were 26.2ppt and 24.3ppt, respectively. At Outer Island, the salinity in August and September was 27.1ppt and 24.8ppt, respectively. It is possible that salinity may have impacted the disparity of gender ratios on the sampling dates, but more studies focusing on the effect of salinity on Asian shore crabs need to be investigated.

A more common Male:Female gender ratio for Asian shore crabs is 2:1, 3:1, and 4:1 (Table 1). In Casanova (1998), gender ratios of about 3:1 in August and 1:1 in October were noted at Outer Island. Jouett and Child (2014) in Johnston, RI noted gender ratios of 1:1. A two-day field survey conducted off the coast of Cape Cod, MA by Benoit et al. in (2005) had ratios of about 1:1 and 1:3 in favor of females. At Stonington Point in this study, a Male:Female gender ratio of 2:1 was observed. While sampling, any crabs that escaped the 1m² plot were left

Table 3. Outer Island *Hemigrapsus sanguineus* Male:Female Gender Ratios

Asian shore crab data collected from Virginia Baltay were by students. The students were in groups of 2-3 and randomly collected 10 crabs in a one-meter square plot.

Data collected by Steven Rodriguez was done using a one-meter square plot. All crabs in the plot were collected if possible.

Data Set	**Date**	**Ratio Male to Female**	**Total males**	**Total females**
V. Baltay	May 2012	2:1	162	85
	June 2012	2:1	142	78
	September 2012	2:1	19	11
	September 2013	3:1	166	49
	June 2014	10:1	10	0
	June-August 2015	3:1	472	172
	June-August 2016	2:1	1358	632
	June-August 2017	4:1	613	142
S. Rodriguez	August 2017	19:1	282	15
	September 2017	8:1	254	31

alone and not counted. It is important to note that the upper MLW levels at the Outer Island and Rye sites had the highest abundances (50% or more of total sample) of shore crabs that were male. Most crabs were collected during sampling. However, a few crabs likely escaped but not enough to significantly impact data that would change the results of this study. Possible errors in classifying gender was not a likely possibility as the differentiation of male and female genders is apparent (Figure 11).   The 0.7- -0.1MLW intertidal zone at all three sites in September (Table 3) were closest to the normal 1:1 Male:Female Asian shore crab ratios seen in other studies.

The disparity shown in the population gender ratio data is better demonstrated when comparing carapace size ranges and male shore crabs (Figure 7). At the Rye site, over 90% of small and large crabs are male. The medium sized crab ratios are roughly equivalent at a 1.5:1 ratio in August and a 3:1 for September. All crabs over 24mm in carapace width were male in both data sets. Similarly, Outer Island small sized shore crabs exceeded 90% in August and September. The medium sized crabs had the closest gender ratios of the entire study at 2.5:1 and 2:1. Stonington Point was the only site to have equivalent gender ratios for all crab sizes (Figure 9). In August, the population gender ratio was 2:1, the CW ratios for small crabs was 2:1 and 1.5:1 for the intermediate range. The gender and CW ratios interestingly had similar results in September at 2:1, and ratios for small sized shore crabs were 3:1 and intermediate crab sizes of 1:1. Despite the disparity in the population gender ratios, the CW size and gender ratios together correlate with other *H. sanguineus* studies (Kraemer et al., 2007).

Figure 11. Sex determination of the Asian shore crab. Photo (a) is a male, notice the narrow abdominal pillar in the middle and that the underbody plate is not completely covered. Photo (b) is a female, the abdominal area is round with horizontal margins and the underside in completely covered.

(a)

(b)

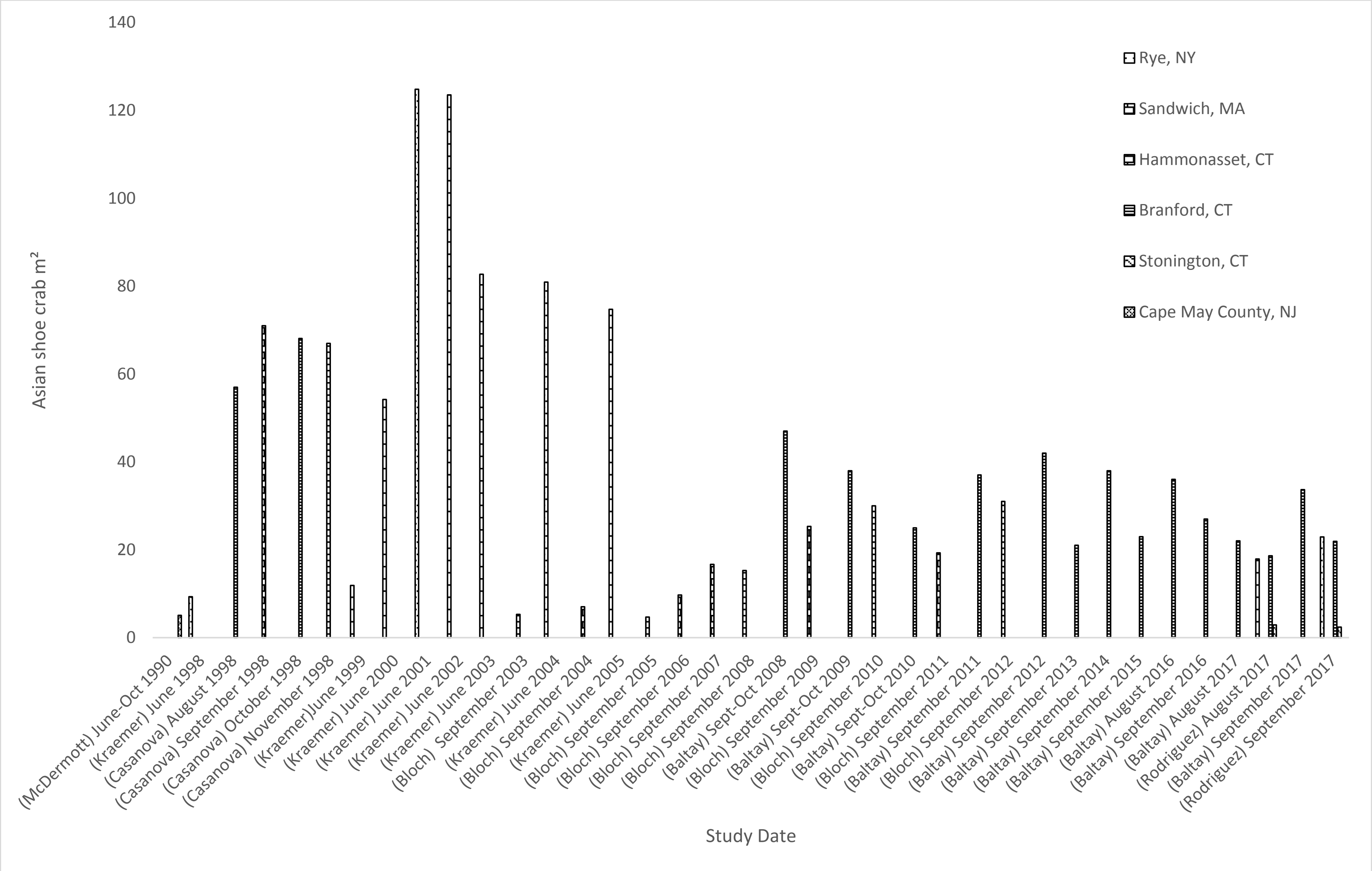
4.5. Regional Shore Crab Population Trends

The results of this study agree with previous studies that show Asian shore crab population densities are stabilizing throughout the region in recent years (Figure 12). Since the first siting of the Asian shore crab in Cape May, New Jersey in 1987, it has become the most abundant shore crab in the northern east coast of the United States (Kraemer et al., 2007; McDermott, 1998b; Westgate, 2011). Published data of *H. sanguineus* first came from McDermott (1991) and population densities increased into the early 2000s (Figure 12). Kraemer et al. (2007) observed some of the highest densities of shore crabs in 2001 and 2002 where crab densities exceeded 123 crabs/m². After 2002, shore crab densities began to trend downward until about 2008 where Baltay (2017) and Bloch et al. (2015) observed stabilizing shore crab densities ranging from 25-42 crabs/m². Results of this study (2017) are shown for comparison and follow trends comparable to Baltay (2017) and Bloch et al. (2015) over the past decade.

Invasive species that greatly increase in abundance and then decrease over time is not uncommon. Studies focusing on the Chinese mitten crab (*Eriocheir sinensis*) have shown this pattern in Germany (Dittel and Epifanio, 2009; Panning, 1939). In the first twenty years following the Chinese mitten crab introduction to Germany, populations increased similarly to the Asian shore crab population growth pattern along the northern east coast of the United States. After twenty years the population of *E. sinensis* declined over the following decade. Declines in the populations of the Chinese mitten crab were also observed in other parts of Europe and in San Francisco Bay on the West Coast of the United States (Schab, 2013; Dittel and Epifanio, 2009).

Invasive species typically follow a series of transitions in a new environment that dictates its success. There are four stages to this sequence: arrival, settlement, expansion and persistence

Figure 12. Trend in Asian shore crab densities (crabs/m²) from all over New England



(Mollison, 1986). In the case of *H. sanguineus*, it arrival in the US came in 1987 and settled relatively quickly. Previous studies have shown a rapid population expansion to abundances at high as 124.5 crabs/m^2 (Figure 11) in 15 years. Once entering the persistence stage in the mid and late 2000s the shore crab population began to stabilize. Trends along northern Long Island Sound and coastal New England show that the population of the Asian shore crab has entered the persistence stage and have stabilized (Figure 12). Any further studies done on the population of *H. sanguineus* in Long Island Sound will most likely yield results that trend similarly to this study and others indicating long-term population stabilization.

Chapter 5.
Conclusion

The Asian shore crab has become the most common crab inhabiting Connecticut shorelines in the last 30 years. Some negative impacts have already been realised as blue mussel declines have resulted in lower harvest for the commercial markets (Brousseau et al., 2014; Bourdeau and O'Connor, 2003), and populations of other native crabs such as the Atlantic blue crab and European green crab have declined (Griffen and Byers, 2009; Roudez et al,. 2007; Payne and Kraemer, 2013). While the results of this study show a decline in abundance, *H. sanguineus* populations are still high and remain the most common crab found along rocky tidal shores in Long Island Sound. Results of this study show similar intertidal shore crab abundances compared to previous studies conducted at Rye and Outer Island. Edith G. Read Wildlife Sanctuary had the highest abundance of shore crabs in the upper intertidal zones of all sample locations. While the lowest abundances of shore crab were found at Stonington Point. The Male:Female gender ratio disparities of 19:1 at Outer Island and 12:1 at the Edith G. Read Wildlife Sanctuary were not comparable with other regional studies. Additional studies should be conducted to further examine the sex ratio disparities found in this study. The results of this study follow similar trends in population density of *H. sanguineus* along the northern Long Island Sound shoreline. A comparison of results of this study with other regional studies show a possible stabilization of the Asian shore crab population over the past decade.

Chapter 6.

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