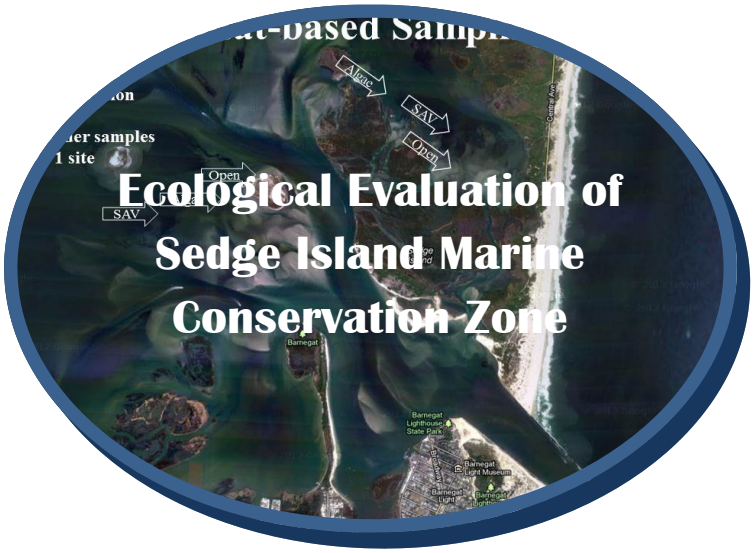
Barnegat Bay—Year 2



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Final Report

Project Title: Ecological Evaluation of Sedge Island Marine Conservation Area in Barnegat Bay

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Executive Summary

Conservation zones are important for maintaining the sustainability of ecosystems and populations of economically important species. The relative ecological value, especially for economically important species, of the Sedge Island Marine Conservation Zone (SIMCZ) in Barnegat Bay, NJ was assessed by comparing the following inside the SIMCZ with areas outside the conservation zone: (1) population structure of adult blue crabs using commercial-style traps, (2) reproductive potential of both sexes and brood production of adult female blue crabs, and (3) species diversity and abundance of fish and select decapod crustaceans, particularly blue crabs, in three habitats (seagrass, macroalgae, and unvegetated) using throw traps. Commercial-style trap sampling indicates that the SIMCZ had greater abundance of male blue crabs, a sex ratio that is more skewed towards males, and a greater proportion of ovigerous females than mid and western-bay locations outside the SIMCZ. There was no evidence that reproductive potential (e.g., sperm stores) or female brood production differed among the locations. Using a complementary data set from a co-occurring project; as compared with physically similar areas,

the SIMCZ contained: (1) more adult blue crabs than other SAV-dominated areas along the north-south axis of Barnegat Bay, (2) more adult females, especially egg-bearing females, than adjacent, SAV-dominated areas with similar access to Barnegat Inlet, and (3) more male blue crabs than open bay habitats within an east-west zone of the Bay. Taken together, these results suggest that the SIMCZ is an important area for both male and female blue crabs, particularly females that are spawning. Throw trap sampling indicates that species diversity, the total abundance of organisms and the abundance of juvenile blue crabs were similar inside the SIMCZ as compared to outside the SIMCZ. In contrast, juveniles of two economically important fish species (winter and summer flounder) were more abundant inside the SIMCZ than outside the SIMCZ. Habitat was far more important than location in accounting for the variation in species diversity, total abundance and the abundance of blue crabs. In general, structured habitats (SAV and algae) contained more species, individual organisms and blue crabs than open areas. Sampling for this project occurred before and after "Superstorm" Sandy, thus annual differences may reflect potential Sandy effects. Annual differences in blue crab abundance between and within locations suggest that the SIMCZ provided a buffer against the potentially negative effects of Sandy. Throw trap sampling suggests that the SIMCZ contains habitats that are ecologically valuable and are helping to sustain valuable species.

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Introduction & Problem Statement

The Sedge Island Wildlife Management Area in Barnegat Bay is located within New Jersey's first Marine Conservation Zone, just off Island Beach State Park. Despite its designation as a Marine Conservation Zone by the Tidelands Council there has been no significant scientific inventory of this environmentally sensitive area, nor an assessment of the essential estuarine habitats in the surrounding conservation zone. Blue crabs are an excellent model organism for assessing the ecological value of the Sedge Island Marine Conservation Zone (SIMCZ). Blue crabs are known to use some of the critical estuarine habitats, such as seagrass, found within the SIMCZ as nursery areas (Jivoff and Able 2001). Fishing and hunting are allowed in NJ's Wildlife Management Areas (NJDEP) during certain seasons and the SIMCZ is adjacent to Barnegat Inlet, where adult female blue crabs potentially congregate in order to spawn (Jivoff, unpublished data); therefore this area may offer minimally disturbed habitats for post-larval crabs and an important refuge from fishing pressure for males and females representing the spawning stock.

The overall goal of the project was to assess the value of the SIMCZ to sustain a key recreational and commercially important species by comparing the following inside the SIMCZ with areas outside the conservation zone: (1) population structure of adult blue crabs using commercial-style traps, (2) reproductive potential of both sexes and brood production of adult female blue crabs, and (3) species diversity and abundance of fish and select decapod crustaceans, particularly blue crabs, in three habitats (seagrass, macroalgae, and unvegetated) using throw traps.

Blue crabs are one of the most important commercial and recreational fisheries in New Jersey (Kennish et al. 1984, Stehlik et al. 1998) and throughout the mid-Atlantic region (Jordan 1998). Historically, during periods of declining crab catches in the Delaware portion of Delaware Bay, the relative importance of blue crab populations in coastal bays like Barnegat Bay increases (NJDEP data). Therefore it is critical to gather information about the population status and key indicators of population sustainability in blue crab populations in estuaries like Barnegat Bay. This project examined facets of the population structure of adult crabs and aspects of adult female reproductive success inside the SIMCZ relative to similar areas outside the SIMCZ to determine the relative importance of the SIMCZ in contributing to population sustainability of blue crabs in Barnegat Bay.

Factors influencing female reproductive output in blue crabs are still not understood. Female blue crabs may produce several broods of fertilized eggs during their reproductive lifetime; however the actual number is still unknown and may be influenced by a variety of factors including female size, food availability and stored sperm supplies (Hines 1982, Prager et al. 1990, Jivoff 2003, Wolcott et al. 2005). Therefore, the seasonal and lifetime fecundity (number of fertilized eggs produced by a female) of blue crabs in New Jersey, near the northern limit of the blue crab range, may vary from that in other locations, requiring different decisions to effectively manage New Jersey blue crabs. In Chesapeake Bay, managers established a marine protected area and corridor, specifically to protect adult female blue crabs enroute and

within their traditional spawning grounds, that provides a refuge from fishing pressure for a considerable portion of the spawning stock (Lipcius et al. 2003). It is unknown whether the SIMCZ provides the same service in Barnegat Bay. This project examined various aspects of brood production of females in the field and attempted to experimentally determine the influence of female size, food level and female location (inside the SIMCZ versus outside the SIMCZ) on various measures of female reproductive output.

Factors influencing post-larval recruitment and the success of juvenile crabs reaching adulthood (i.e., recruiting to the fishery) have been well studied (Wilson et al. 1990, Lipcius et al. 2005, Moksnes and Heck 2006). While some of this work on the success of juvenile crabs has occurred in Little Egg Harbor, the lower portion of Barnegat Bay, there is little to no information on post-larval recruitment of blue crabs in Barnegat Bay proper. One critical factor is the presence of nursery habitats that provide refuge from predation as well as adequate food resources. Many of these habitats including seagrass beds and near-shore shallows are negatively impacted by a variety of human-induced sources including physical impacts (Eckrich and Holmquist 2000) from boat and personal watercraft traffic. Comparing post-larval crab abundance in common habitats inside the SIMCZ (where boat traffic is minimal) with a similar area outside the SIMCZ provides the opportunity to assess the role of the SIMCZ in providing critical habitats for post-larval blue crabs as well as to examine human-induced impacts on blue crab habitat use. This project examined species diversity and abundance of fish and select decapods (e.g., crabs and shrimp) in three shallow-water habitats (seagrass, macroalgae, and unvegetated) both inside and outside the SIMCZ.

Project Design & Methods

Sampling Techniques: Adult Blue Crabs

The objective was to examine the temporal and spatial variation in population characteristics of adult blue crabs including a comparison of population characteristics inside versus outside the SIMCZ. Using a complementary data set from a co-occurring project, population characteristics inside the SIMCZ were also compared with physically similar areas: (1) of the same habitat type (i.e., SAV-dominated) along the north-south axis of Barnegat Bay, and (2) of different habitats along the east-west axis of the Bay. Sampling (for both projects) was done using baited (with menhaden) commercial-style traps sampled daily for four consecutive days during each month (May-August 2012 and 2013). Traps had consistent “soak times” and bait was replaced daily. Sampling occurred in 3 areas that spanned the width of Barnegat Bay (inside the SIMCZ on the eastern shore of the Bay, in mid-Bay, and on the western shore of the Bay) (Figure 1). Each of the three sampling areas contained 4 replicate sampling sites (Figure 1). Each sampling day, three traps were randomly assigned to one of the four sampling sites within each area and placed at least 50m apart from one another. Crabs were separated by trap in moistened burlap bags, returned to the Rutgers University Marine Field Station, and measured for carapace width, sex, age-class, sexual maturity, molt stage, limb loss (i.e., a non-regenerated limb) and regeneration

(i.e., presence of a limb bud), and ovigerous stage (adult females). Sexual maturity and molt stage were determined using previously established methods (Jivoff 1997). Physical characteristics including depth, salinity, temperature, and dissolved oxygen were taken with a hand-held YSI datalogger (model 6820 in 2012, 6920 in 2013) at the first and last trap in each sampling location. Depth was also measured with a depth pole marked at 10cm increments and verified using the YSI. The time and tidal stage were also noted. Dependent variables (e.g., total, male and female abundance) were analyzed using a three-way ANOVA with year, month and location as independent variables. The proportion of ovigerous females between locations was examined using a χ^2 test.

Sampling Techniques: Field Experiment

The objective was to examine the factors influencing the number, size and timing of broods produced by adult female blue crabs including female size, food, and if captured inside or outside the SIMCZ. Ovigerous females (i.e., those carrying fertilized eggs) were collected in May (thus presumably carrying their first brood of eggs) and held individually in field enclosures partially submerged in the sediment and accessible at low tide (Dickinson et al. 2006) to assess the following factors on the incidence, size, and timing of broods produced: capture location (inside SIMCZ versus outside SIMCZ), carapace width (small, $\leq$125mm; medium, 130-140mm; and large $\geq$145mm), and food level (low=fed once per week or high=fed three times per week). Food levels were based on crabs receiving approximately 100g of fish, primarily menhaden, at each feeding. The enclosures were checked three times per week; fouling organisms (e.g., algae) were removed when necessary and females were examined for the presence of a new brood of eggs. The size of each new brood was assessed using previously established techniques (Dickenson et al. 2006 [pp 274-276]). Briefly, the size of broods was assessed by measuring the dimensions of the overall brood: width (laterally at the middle of the brood), length (vertically at the middle of the brood) and depth (thickness of the brood between the ventral surface of the female's carapace and the inside of the ventral flap). The proportion of females producing at least one brood between locations was examined using a χ^2 test.

Sampling Techniques: Reproductive Potential Studies

A daily sample of adult crabs ($n \geq 12$ of each sex) and of ovigerous females ($n \geq 12$) across 6 size classes (100-109, 110-119, 120-129, 130-139, 140-149 and $\geq$150) from each site were combined in a plastic bag with a label indicating the date, sampling location and site of collection and placed in a freezer (located at the Rutgers Field Station) for subsequent dissection and measurement of reproductive potential using previously established techniques: sperm stores and seminal fluid weight in males; sperm stores, ovarian weight and developmental stage, brood stage and egg number in females. Dependent variables (e.g., male spermatophore weight, male seminal fluid weight, female seminal receptacle weight, female ovary weight) were analyzed using a two-way ANOVA with year and location as independent variables.

Sampling Techniques: Species Diversity and Abundance of Fish and Select Decapods
The objective was to examine the temporal and spatial variation in the species diversity and abundance of fish and select decapod crustaceans, particularly blue crabs, among three common estuarine habitats existing inside and outside the SIMCZ. Sampling was performed using quantitative samplers (i.e., throw traps) deployed daily for four consecutive days during each month (May-August 2012 and 2013) and two consecutive days in September (2012 and 2013). Sampling was performed in two areas: inside the SIMCZ and outside the SIMCZ (Figure 2). Each area contained four replicate sampling sites with each site containing the three habitats: seagrass, macroalgae, and unvegetated (Figure 2). Each sampling day, one of the sampling sites in each area was chosen at random and two throw trap sets were performed in each habitat. Throw traps were circular (1.12m diameter x 0.84m tall) and enclosed a 1.0m^2 area. Long-handled dip nets with fine mesh were used to sweep the benthos (and nekton) enclosed by the throw trap. Sweeps ended when nothing was captured after five successive sweeps. The catch was processed in the field: fish and shrimp were identified to species and total length (of 21 individuals) was measured; crabs were measured for carapace width, sex, age-class, sexual maturity, molt stage, limb loss and regeneration, and ovigerous stage (adult females). Physical characteristics including depth, salinity, temperature, and dissolved oxygen were taken with a hand-held YSI datalogger (model 6820 in 2012, 6920 in 2013) at each throw trap set. Depth was also measured with a depth pole marked at 10cm increments and verified using the YSI. The time and tidal stage were also noted. Dependent variables (e.g., number of species, total abundance, abundance of blue crabs) were analyzed using a four-way ANOVA with year, month, location and habitat as independent variables. Annual and location differences in the size frequency of crabs were examined using the Kolmogorov-Smirnov test.

Quality Assurance
The YSI 6820 and 6920 handheld data loggers, which record temperature, salinity, and dissolved oxygen, are calibrated before and after each field sampling. All water quality testing is performed by a New Jersey laboratory certified person under the requirements of N.J.A.C. 7:18 or laboratories which have formal approval from the NJDEP-Office of Quality Assurance. Certificates of formal approval are specific to the QAPP related analytical testing and are effective until June 30th of every year.

Results & Discussion

Results: Trap Sampling (Adult Blue Crabs)
Abundance patterns differed between the sexes, thus separate analyses examining the abundance of each sex were conducted. The abundance of males varied by month ($F_{3,255}$=41.03, P<0.001), and location ($F_{2,255}$=49.26, P<0.001). Overall, more adult male blue crabs were captured in the SIMCZ than either location outside the SIMCZ and the ratio of males to females was also greater inside the SIMCZ as compared to either location outside the SIMCZ (Figure 3). Each location

exhibited a similar monthly pattern in male abundance with average male abundance increasing from May-July followed by a decrease in August. The monthly differences among the locations were relatively consistent; in each month more males were captured in the SIMCZ and along the western shore than in the mid location. The abundance of females was more variable than males; varying by year ($F_{1,255}$=41.32, P<0.001), month ($F_{3,255}$=8.23, P<0.001), and location ($F_{2,255}$=4.43, P=0.01). Overall, females were slightly more abundant at the mid location than the SIMCZ but neither the differences among the months at each location nor the differences among locations in each month exhibited a recognizable or consistent pattern. Neither the average size of males ($F_{2,755}$=3.09, P=0.05) nor of females ($F_{2,529}$=0.91, P=0.40) was significantly different among the locations. In the SIMCZ, more adult females were ovigerous than expected relative to both the mid (χ^2, P=0.004) and the west (χ^2, P=0.01) locations. These data suggest that the SIMCZ is important to both adult male blue crabs as well as adult females, especially spawning females.

There was statistically significant variation in temperature ($F_{2,156}$=19.62, P<0.001), salinity ($F_{2,156}$=8.53, P<0.001), and depth ($F_{2,156}$=46.56, P<0.001) among the locations during the sampling period. However, on average, the absolute magnitude of the differences in temperature and salinity (<2°C, <1ppt, respectively) and the range of salinity values among the locations (28-29ppt) suggest these physical differences may not adequately explain the spatial variation in abundance or sex ratio described above. Consistent with the throw trap sampling (see below), the SIMCZ was shallower than both areas outside the SIMCZ (Tukey HSD, P<0.001 for both comparisons). However, on average, the absolute magnitude of these differences (~50cm) and the range of depths among locations are well within those used by adult blue crabs. The replicate sites within the locations, particularly the two locations outside the SIMCZ, may have varied somewhat in habitat type whereas the SIMCZ is dominated by submerged aquatic vegetation (SAV). Therefore, to avoid the potentially confounding effect of habitat and to compare the SIMCZ with wider array of sites, a complementary data set was used to examine adult blue crab population characteristics inside the SIMCZ relative to areas outside the conservation zone.

In collaboration with Kenneth Able at the Rutgers University Marine Field Station, we also participated in a project examining population characteristics of blue crabs in response to human urbanization in Barnegat Bay. For that project we sampled, also using blue crab traps, in four major estuarine habitats (open bay, SAV and the mouths of two types of creeks-high urbanization and low urbanization creeks) in each of five areas that encompassed virtually the entire length of Barnegat Bay (see Figure 4) over the same time period as the Sedge Island project. Therefore, in addition to the analysis above, blue crab population characteristics were also compared between the SIMCZ and physically similar (particularly salinity) areas containing (1) the same habitat along the north-to-south axis of the bay, and (2) different habitats within an east-to-west section of the bay. As such, only areas I, II and III (see Figure 4) were used in this analysis due to physical characteristics (especially salinity) shared with the SIMCZ.

The SIMCZ is dominated by SAV; in comparison to other areas dominated by SAV, the total abundance of crabs in the SIMCZ was greater than all three areas (areas I, II, and III, see Figure 4) sharing physical characteristics (Figure 5). Within SAV-dominated habitats, the

relative abundance of the sexes helps explain the differences between the SIMCZ and these other areas. As compared to area I (the southern-most area), the SIMCZ contained more males (Figure 5). The similarity in the number of females between the SIMCZ and area I may be due to both areas' proximity to an inlet (SIMCZ to Barnegat Inlet and area I to Little Egg Inlet) where adult females spawn. As compared to area II, the SIMCZ contained more males and females, but as compared to adjacent SAV-dominated habitats in area III, the SIMCZ contained more females despite a similar proximity to Barnegat Inlet (Figures 5). In addition, the SIMCZ contained more ovigerous females than expected as compared to adjacent SAV-dominated sites in area III (χ^2, $P<0.001$). This variation in SAV-dominated habitats along the north-south axis of the bay suggests that the SIMCZ is unique for its importance to both female, particularly spawning females, and male blue crabs in Barnegat Bay.

In comparison to different habitats sharing physical characteristics, the total number of crabs was greater in the SIMCZ as compared to open bay habitats in all three areas (areas I, II, and III, see Figure 4) sharing physical characteristics (Figure 6). Again, differences in the relative abundance of the sexes help explain the variation between habitats. In general, the SIMCZ contains more male crabs as compared to open bay habitats. Despite its proximity to Barnegat Inlet, leading to the expectation that the SIMCZ is important for female blue crabs, the SIMCZ is also an important area for male blue crabs compared to one other common bay habitat.

Results: Reproductive Potential Studies

Adult females from inside and outside the SIMCZ were held in field enclosures under two conditions; high diet and low diet, to examine the influence of location and diet on brood production. In 2012, a delay in getting the field experiment established as well as mortality of adult females limited the amount of data collected on brood production from this experiment. Several females produced broods during the experiment but we have no data on individual females producing multiple broods. In 2013, fourteen females produced at least one brood during the experiment; location (inside SIMCZ versus outside) did not influence the proportion of females that produced at least one brood. However, in females from outside the SIMCZ, more receiving the high diet than expected produced at least one brood compared to the low diet treatment (χ^2, $P=0.004$). Females from the SIMCZ exhibited this pattern but low sample size may have prevented statistical significance.

In adult females, measures of reproductive potential include ovary weight (a proxy of available eggs for future brood production) and seminal receptacle weight (a proxy of available sperm for future egg fertilization). A female's temporal proximity to copulation can influence both ovary weight (low for recently mated females but high for females closer to spawning) and seminal receptacle weight (high for recently mated females but low for females closer to spawning). Indeed, ovary weight did not vary by location ($F_{2,279}=0.95$, $P=0.39$), however females with early-stage ovaries had significantly lighter ovaries than females with late-stage ovaries ($F_{1,279}=97.49$, $P<0.001$) and this pattern was repeated in each location. Female seminal receptacle weight did not vary by location ($F_{2,279}=1.15$, $P=0.32$) but females with early-stage

ovaries had significantly heavier seminal receptacles than females with late-stage ovaries ($F_{1,279}$=4.37, P=0.04).

In adult males, measures of reproductive potential include weights of the vas deferens components that are passed to females during copulation; spermatophores and seminal fluid. Neither the average weight of male spermatophores ($F_{2,334}$=0.81, P=0.44) nor that of male seminal fluid ($F_{2,330}$=1.76, P=0.17) varied among the locations.

Results: Throw Trap Sampling (Species Diversity and Abundance of Fish and Select Decapods)
The total number of species of fish (17) and decapods (12) captured in the SIMCZ was similar to the number of species of fish (18) and decapods (15) captured outside the SIMCZ (Table 1). Both inside and outside the SIMCZ, structured habitats (algae and SAV) contained a greater number of species (Table 1 and Figure 7) and had larger Shannon-Weiner Indexes (S-W) (Table 1) than the open habitat. In both locations, S-W values were slightly higher in algae than in SAV and the S-W values in both vegetated habitats were slightly higher outside the SIMCZ than inside the SIMCZ (Table 2). The S-W index incorporates both species richness (number of species) and evenness (relative abundance of each species). Therefore, the indexes of the open habitats were relatively low compared to the structured habitats because while several species may have been captured in open habitats, only one or two (e.g., sand shrimp) numerically dominate open habitats (Table 2). While there were a few species that were relatively common in both structured habitats (e.g., sand shrimp, grass shrimp, mud crabs), S-W values in algae were slightly higher than SAV because rarer species were more uniform in abundance (Table 2). In contrast, the average number of species in SAV was slightly, but significantly, higher than in algae both inside and outside the SIMCZ (Figure 7). This suggests that while species richness is greater in SAV, species evenness is greater in algae and this is common between the locations. The lack of obvious differences in species richness and evenness between the locations also suggests that the SIMCZ is at least equivalent to a comparable area outside the SIMCZ.

The number of species varied significantly by month ($F_{4,354}$=12.45, P<0.001), location ($F_{1,354}$=4.39, P=0.04) and habitat ($F_{2,354}$=365.87, P<0.001), with habitat accounting for the most variation (58%). While statistically significant, the average number of species outside the SIMCZ (4.63 $\pm$ 2.84SD) was only slightly larger than inside the SIMCZ (4.31 $\pm$ 2.57SD). The monthly variation in the number of species differed slightly between the years (year x month interaction, $F_{4,354}$=6.68, P<0.001) with the average number of species rising from a low in May to a plateau that began in July in 2013, as compared to June in 2012. The monthly variation in the number of species also differed among the habitats (month x habitat interaction, $F_{8,354}$=4.91, P<0.001) such that the number of species found in both structured habitats increased between May and August while the number of species found in open habitats remained consistently low during those months (Figure 7). It is interesting to note that in each month, the average number of species in SAV was slightly greater (with differences being statistically significant in May, July and August) than in algae (Figure 7). Again, the absence of obvious differences in the number of species between the locations suggests that the SIMCZ is at least equivalent to a comparable area outside the SIMCZ.

The abundance of all organisms varied significantly by month ($F_{4,354}$=14.70, P<0.001) and habitat ($F_{2,354}$=433.98, P<0.001) with habitat accounting for the most variation (50%). The monthly variation differed between the years with a more distinct monthly increase in abundance between May and July occurring in 2013 than in 2012. Abundance among the habitats varied by year (year x habitat interaction, $F_{2,354}$=5.09, P=0.01) and by month (month x habitat interaction, $F_{8,354}$=11.94, P<0.001). Both vegetated habitats had reduced abundance in 2013 as compared to 2102 while open habitats did not vary significantly between years. Each habitat exhibited a different monthly pattern in abundance: open areas had consistently low abundance from May-September; algae habitats showed an increase in abundance from May to June then remained steady until September; whereas SAV habitats showed a monthly increase in abundance from May to July followed by another increase in abundance in September (Figure 8). Location was not a contributing factor to the variation in the abundance of all organisms suggesting that overall the SIMCZ is at least equivalent to a comparable area outside the SIMCZ.

One goal of the conservation zone is to help sustain commercially and recreationally important species, thus blue crabs were a key target organism of this research. Other harvested species were also captured both inside and outside the SIMCZ. Two species of flounder (winter and summer) were captured in throw traps, and while the absolute numbers limited the type of statistical analysis that could be performed, they deserve comment here. More summer flounder were captured inside the SIMCZ, especially in SAV, than expected relative to outside the SIMCZ (χ^2, P=0.028) and more winter flounder were also captured inside the SIMCZ, in both vegetated habitats, than expected relative to outside the SIMCZ (χ^2, P<0.001).

The abundance of blue crabs varied significantly by year ($F_{1,354}$=19.01, P<0.001), month ($F_{4,354}$=23.00, P<0.001), location ($F_{1,354}$=15.39, P<0.001), and habitat ($F_{2,354}$=85.35, P<0.001) with habitat accounting for the most variation (18.5%). Significant interactions occurred between the main effects including a year x month x location x habitat interaction ($F_{8,354}$=3.81, P<0.001) reducing the relative importance of the individual main effects and indicating that a complex set of factors contributes to the abundance of blue crabs. Within each location, more crabs were captured in SAV and algae as compared to open areas and more crabs were captured in SAV as compared to algae (Figure 9). Within open and algae habitats, similar numbers of crabs were captured inside versus outside the SIMCZ, however, more crabs were captured in SAV outside the SIMCZ as compared to inside the SIMCZ (Figure 9). Incorporating size information is useful for interpreting the variation in abundance. Size frequency distributions revealed two distinct time periods between May and September with each time period dominated by a distinct life history stage of blue crabs: May-July was typically dominated by juveniles (i.e., year 1 crabs, >20mm) and August-September was dominated by recruits (i.e., year 0 crabs, <20mm) (Figure 10). Indeed, in each year and location, the size frequency distribution of crabs differed significantly between these two time periods (two-sample KS tests, all P<0.001). The only exception occurred in 2013, outside the SIMCZ (KS test, P=0.07) which showed the same trend but relatively low sample size may have prevented statistical significance.

Data from 2012 were obtained before "Superstorm" Sandy whereas data from 2013 were obtained after "Superstorm" Sandy; thus annual differences may reflect a potential Sandy effect. In both years, blue crab abundance differed between the locations but the direction of the differences was reversed. In 2012, there were more blue crabs than expected outside the SIMCZ relative to inside the SIMCZ (χ^2, $P<0.001$) whereas in 2013, there were more blue crabs than expected inside the SIMCZ relative to outside the SIMCZ (χ^2, $P=0.037$) (Figure 10). This difference suggests that the SIMCZ may have buffered possible harmful effects of Sandy on juvenile blue crabs. Similarly, outside the SIMCZ, there were significantly fewer blue crabs than expected in 2013 as compared to 2012 (χ^2, $P<0.001$), however, inside the SIMCZ, blue crab abundance was similar between the years (Figure 10). This also suggests that the SIMCZ may have buffered potential harmful effects of Sandy on juvenile blue crabs.

In order to test the relative importance of biological factors (e.g., habitat quality) on species diversity and organism abundance inside the SIMCZ, the conservation zone must be compared with an area that is physically similar to the SIMCZ to minimize the influence of physical factors. The SIMCZ and the area outside the SIMCZ were very similar with respect to temperature, salinity, dissolved oxygen and depth. There was considerable variation in all of the physical variables but the factor most influential in explaining this variation was month (68.3% for temperature, 30% for salinity, 12.6% for dissolved oxygen) with location and/or habitat explaining very little of the variation in any of the physical variables. The one exception was depth; habitat explained 31.1% of the variation in depth, primarily because in each location, the open habitats were consistently shallower than either of the vegetated habitats. It should be noted that while statistically significant amounts of variation could be attributed to various factors, the absolute differences in physical variables was very small, the values of physical variables fell within the tolerance ranges of mid-Atlantic organisms, and with respect to dissolved oxygen, levels were not limiting. Furthermore, none of the physical variables were significant covariates in explaining variation in the abundance of all organisms or in the number of species. Taken together, the results suggest that the two locations were physically very similar and that physical variables were relatively unimportant in explaining the spatial differences in species diversity and organism abundance described above.

Conclusions and Recommendations for Future Research

Commercial-style trap sampling indicates that the SIMCZ had greater abundance of male blue crabs, a sex ratio that is more skewed towards males, and a greater proportion of ovigerous females than areas outside the SIMCZ. Using a complementary data set to compare the SIMCZ with a spatially-broader array of sites, the SIMCZ contained: (1) more adult blue crabs than other SAV-dominated areas along the north-south axis of Barnegat Bay, (2) more adult females, especially egg-bearing females, than adjacent, SAV-dominated areas with similar access to Barnegat Inlet, and (3) more male blue crabs than open bay habitats within an east-west zone of the Bay. Taken together, these results suggest that the SIMCZ is unique as an important area for both male and female blue crabs, particularly females that are spawning. One potential impact of

the lack of commercial fishing inside the SIMCZ (especially during the summer) may be a preponderance of males since more males are taken by the commercial fishery at this time of year. Thus, relaxed fishing pressure may benefit male blue crabs and skew the adult sex ratio towards males inside the SIMCZ. Due to the relative abundance of ovigerous females, the SIMCZ may also represent an important area for the spawning stock of blue crabs in Barnegat Bay. In order to test the idea that adult crabs benefit from reduced fishing pressure in the SIMCZ, it would be necessary to gauge the "residence time" of adult crabs in the SIMCZ. In the future, one way to measure how long adult crabs remain in the SIMCZ would be via tag-recapture techniques comparing movement and/or residency of tagged crabs inside versus outside the SIMCZ.

Throw trap sampling indicates that species diversity, the total abundance of organisms and the abundance of juvenile blue crabs were similar inside the SIMCZ as compared to outside the SIMCZ. However, juveniles of two economically important fish species (winter and summer flounder) were more abundant inside the SIMCZ than outside the SIMCZ. These results suggest that the SIMCZ contains habitats that are ecologically valuable, and similar in value to outside areas, that are helping to sustain valuable species. The physical characteristics are similar in the two locations used in this study, but one factor that may influence the abundance of blue crabs and other species in these areas is the recruitment of early life history stages to these areas. The area outside the SIMCZ is inundated directly with water entering the estuary via Barnegat Inlet whereas this water must travel through marsh channels of various sizes to reach much of the SIMCZ (see Figure 2). As a result, early life history stages of organisms carried into the estuary via Barnegat Inlet may have more direct access to the area outside the conservation zone. In the future, one way to test this idea would be to measure the relative abundance of early life history stages (e.g., megalopae) of blue crabs being delivered to habitats inside versus outside the SIMCZ using megalopae collectors.

"Superstorm" Sandy occurred between the two years of this project, thus annual differences may reflect potential Sandy effects. Two pieces of evidence suggest juvenile blue crabs were negatively affected by Sandy: (1) reduced abundance in 2013 (post-Sandy) as compared to 2012 (pre-Sandy) with this reduction only occurring outside the SIMCZ, and (2) a reversed pattern of abundance at the locations between years with greater abundance inside the SIMCZ versus outside in 2013 (post-Sandy). Both of these results suggest that the SIMCZ, because the major habitats are protected by the marshes of the Sedge Islands, provided a buffer for juvenile blue crabs against the potentially negative effects of Sandy. Evidence that Sandy had an effect on other organisms includes the year x month interaction seen in the number of species and the total number of organisms; both showed lower values in May of 2013 (post-Sandy) as compared to May of 2012 (pre-Sandy), and both took longer to reach the summer-time peak value in 2013 (July) as compared to 2012 (June). As with juvenile blue crab abundance, there is some evidence that the total number of organisms was less impacted inside the SIMCZ as compared to outside. Outside the SIMCZ, the total number of organisms in May of 2013 was 67% less than May of 2012, whereas inside the SIMCZ there was a 50% drop after Sandy. All

of the evidence presented above for negative effects of Sandy is suggestive; Sandy may not be the sole explanation for these patterns. In addition, especially for the total number of species and number of organisms, the evidence suggests that the negative effect of Sandy was temporary; both factors exhibited relatively rapid recovery to pre-Sandy levels. Thus, Barnegat Bay and its inhabitants showed resilience in response to a potent ecological disturbance.

Evidence indicates that the effects of marine reserves (i.e., "no-take" zones or marine protected areas "MPAs"), including enhanced species diversity and increased abundance and size of protected species, become more apparent overtime (Shears et al. 2006, Barrett et al. 2009, Edgar et al. 2009, Molloy et al. 2009, Stobart et al. 2009). It has been suggested that a reserve must be maintained for at least 15 years, even if it appears to be ineffective, to determine its true impact (Molloy et al. 2009). Thus, in order to understand the impact of a marine reserve, long-term monitoring is necessary. The overall sampling design used in this research, comparing various response variables inside the conservation zone with a equivalent area outside the zone, is consistent with the majority of studies examining the effectiveness of marine reserves (Lester et al. 2009, Molloy et al. 2009) and should continue. One specific aspect of the sampling design that should continue is the use of quantitative sampling devices (throw traps) rather than other traditional gears (e.g., trawls). Quantitative samplers are considered preferable to other gears for shallow, estuarine habitats because they are consistently efficient among habitats and individual samples are comparable (Rozas and Minello 1997). In addition, they are less destructive to benthic habitats than trawls (Watling and Norse 1998), which should be a higher priority for gear choice when sampling in a marine reserve. One specific aspect of the sampling design that should be altered for long-term monitoring is the frequency of sampling. The current design included monthly sampling from May-September. However, I suggest that sampling frequency should be seasonal; for example spring (April or May), summer (July or August) and fall (September or October). With less effort, this would more effectively capture (1) ontogenetic shifts of residents across a wider temporal scale and (2) recruitment events of different organisms whose peak recruitment to the estuary varies temporally. Another specific aspect of the sampling design that could also be altered for long-term monitoring is the number of habitats sampled. Rather than the three used in this study (SAV, algae and open areas), sampling could be confined to one (e.g., SAV) but additional measures of habitat quality (e.g., blade density, blade length, epiphytic coverage) could be taken to insure habitat quality is not a confounding effect and, especially in the case of SAV characteristics, as a barometer of water quality.

Recommendations and Application and use by NJDEP

Overall, the results suggest that the SIMCZ provides valuable habitats (of similar quality to a comparable area outside the conservation zone) to a variety of species including the economically valuable blue crab. Considering the lack of previous scientific inventory in the SIMCZ, the NJDEP now has quantitative validation for the historical designation of this area as a conservation zone and justification for this continued designation as well as future protection of the conservation zone. The SIMCZ is similar to what is known as a partially protected area

(PPA), in that some extractive activities are allowed in the SIMCZ, as opposed to a "no-take zone" or fully protected marine protected area (MPA) where none of these activities are permitted (Lubchenco et al. 2003, Lester and Halpern 2008). Research examining the effectiveness of protected areas, whether for conservation or enhanced fisheries, suggests that spatially small and/or isolated areas are more effective if multiple areas can be "combined" into a network of reserves that are biologically connected via larval dispersal or movement of older life history stages (Lubchenco et al. 2003, Gaines et al. 2010). Designing effective protected areas requires a combination of both abiotic (e.g., physical characteristics, benthic topography) as well as biotic (e.g., species diversity, organism abundance) information (Friedlander et al. 2003, Ban 2009). The current project has provided both types of information for the SIMCZ. In addition, a wealth of abiotic and biotic information about Barnegat Bay is being accumulated by various research projects as part of the NJDEP's Barnegat Bay Action Plan. Concomitantly, NJDEP has identified several "ecologically sensitive" areas in Barnegat Bay that may warrant future protection because they contain critical habitats that may be subjected to various human impacts. All of this information could be used to determine if combining these (or any other) ecologically sensitive areas with the SIMCZ to form a network of conservation zones within Barnegat Bay would increase the SIMCZ's effectiveness and enhance the conservation benefits to the Bay.

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Appendices

Results from this research were presented at the annual Fall meeting of the Atlantic Estuarine Research Society as an oral presentation entitled: "The relative ecological value of the Sedge Island Marine Conservation Zone in Barnegat Bay, NJ." by Jivoff, P., Kels, J., McCarthy, J. Moritzen, L, Young, A.

Figures & Tables

Table 1. Abundance of each species captured via throw trap in each habitat inside and outside of the SIMCZ, May-September 2012 and 2013.

		Inside SIMCZ			**Outside SIMCZ**			
		Habitat			**Habitat**			
Common Name	**Species Name**	**open**	**algae**	**sav**	**open**	**algae**	**sav**	**Total**
Fish								
4-spine stickleback	*Apeltes quadracus*	7	260	799	8	94	445	1613
American eel	*Anguilla rostrata*			5		2	1	8
bay anchovy	*Anchoa mitchilli*					1		1
black sea bass	*Centropristis striata*		1			3	2	6
conger eel	*Conger oceanicus*		1	3		1		5
cunner	*Tautogolabrus adspersus*		4	6		17	10	37
feather blenny	*Hypsoblennius hentz*		1					1
mummichog	*Fundulus heteroclitus*		1	3				4
naked goby	*Gobiosoma bosc*	4	35	5	2	65	21	132
oyster toadfish	*Opsanus tao*		2				2	4
pinfish	*Lagodon rhomboides*						1	1
pipefish	*Syngnathus fuscus*	1	17	13	2	28	49	110
seaboard goby	*Gobiosoma ginsburgi*		2			9	2	13
seahorse	*Hippocampus erectus*					1	1	2
silver hake	*Urophycis regia*				1			1
silver perch	*Bairdiella chrysoura*		2	7			4	13
silverside	*Menidia menidia*	17	60	5	6	25	2	115
summer flounder	*Paralichthys dentatus*		3	18	4	2	3	30
tautog	*Tautoga onitis*			2		5	4	11
tomcod	*Microgadus tomcod*					1		1
winter flounder	*Pleuronectes aamericanus*	14	43	51	13	17	22	160
yellowtail flounder	*Pleuronectes ferruginea*			12				12
Decapods								
blue crab	*Callinectes sapidus*	3	75	132	13	143	216	582
grass shrimp	*Palaemonetes pugio*		466	1340	1	268	1067	3142
green crab	*Carcinus maenas*		55	79	1	96	49	280
green shrimp	*Hippolyte sp.*		117	338	3	170	308	936
horseshoe crab	*Limulus polyphemus*					1		1
Japanese shore crab	*Hemigrapsus sanguineus*						1	1
lady crab	*Ovalipes ocellatus*	4	2		2	1		9
Lesser blue crab	*Callinectes similis*				1			1
long nose spider crab	*Libinia dubia*		4	4	3	72	7	90
mud crab	*Neopanopeus sayii*	3	324	526	1	394	771	2019
mud shrimp	*Callianassa atlantica*		1				3	4
pea crab	*Pinnixia sp.*	2	6	3		8	2	21
rock crab	*Cancer irroratus*	13	79	23	4	249	50	418
sand shrimp	*Crangon septemspinosa*	543	962	194	653	859	599	3810
spider crab	*Libinia emarginata*	2	14	8	2	111	23	160
Habitat Total		**625**	**2538**	**3576**	**728**	**2644**	**3666**	**13777**
Number of Species		**12**	**27**	**23**	**19**	**28**	**28**	**40**
Shannon-Weiner Index		**0.59**	**1.97**	**1.82**	**0.55**	**2.24**	**1.97**	

Table 2. Relative proportion of the 10 most abundant species captured via throw trap in each habitat inside and outside of the SIMCZ, May-September 2012 and 2013. The cumulative percentage of the total number of organisms captured is also shown.

Inside SIMCZ						Outside SIMCZ					
Species	**Open**	**Species**	**Algae**	**Species**	**SAV**	**Species**	**Open**	**Species**	**Algae**	**Species**	**SAV**
sand shrimp	88.6	sand shrimp	37.9	grass shrimp	37.5	sand shrimp	90.6	sand shrimp	32.5	grass shrimp	29.1
silverside	2.8	grass shrimp	18.4	4-spined stickleback	22.3	blue crab	1.8	mud crab	14.9	mud crab	21.0
winter flounder	2.3	mud crab	12.8	mud crab	14.7	winter flounder	1.8	grass shrimp	10.1	sand shrimp	16.3
rock crab	2.1	4-spined stickleback	10.2	green shrimp	9.5	4-spined stickleback	1.1	rock crab	9.4	4-spined stickleback	12.1
4-spined stickleback	1.1	green shrimp	4.6	sand shrimp	5.4	silverside	0.8	green shrimp	6.4	green shrimp	8.4
naked goby	0.7	rock crab	3.1	blue crab	3.7	rock crab	0.6	blue crab	5.4	blue crab	5.9
lady crab	0.7	blue crab	3.0	green crab	2.2	summer flounder	0.6	spider crab	4.2	rock crab	1.4
blue crab	0.5	silverside	2.4	winter flounder	1.4	green shrimp	0.4	green crab	3.6	green crab	1.3
mud crab	0.5	green crab	2.2	rock crab	0.6	long nose spider crab	0.4	4-spined stickleback	3.6	pipefish	1.3
spider crab	0.3	winter flounder	1.7	summer flounder	0.5	pipefish	0.3	long nose spider crab	2.7	spider crab	0.6
Cumulative %=	**99.6**	**Cumulative %=**	**96.3**	**Cumulative %=**	**97.8**	**Cumulative %=**	**98.4**	**Cumulative %=**	**92.8**	**Cumulative %=**	**97.4**

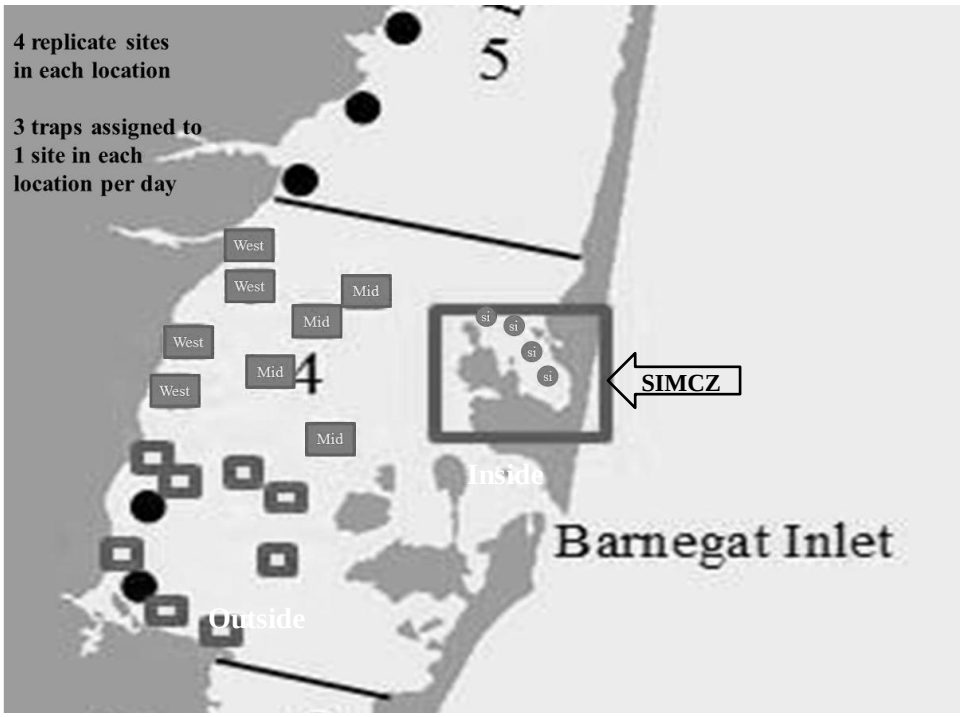

Figure 1. Approximate locations of trap sampling sites. The three locations are "west", "mid" and "si". The other symbols do not pertain to this study. The arrow indicates the SIMCZ.

Figure 2. Approximate locations of throw trap sampling sites inside and outside the SIMCZ. s=SAV, a=Algae, o=Open.

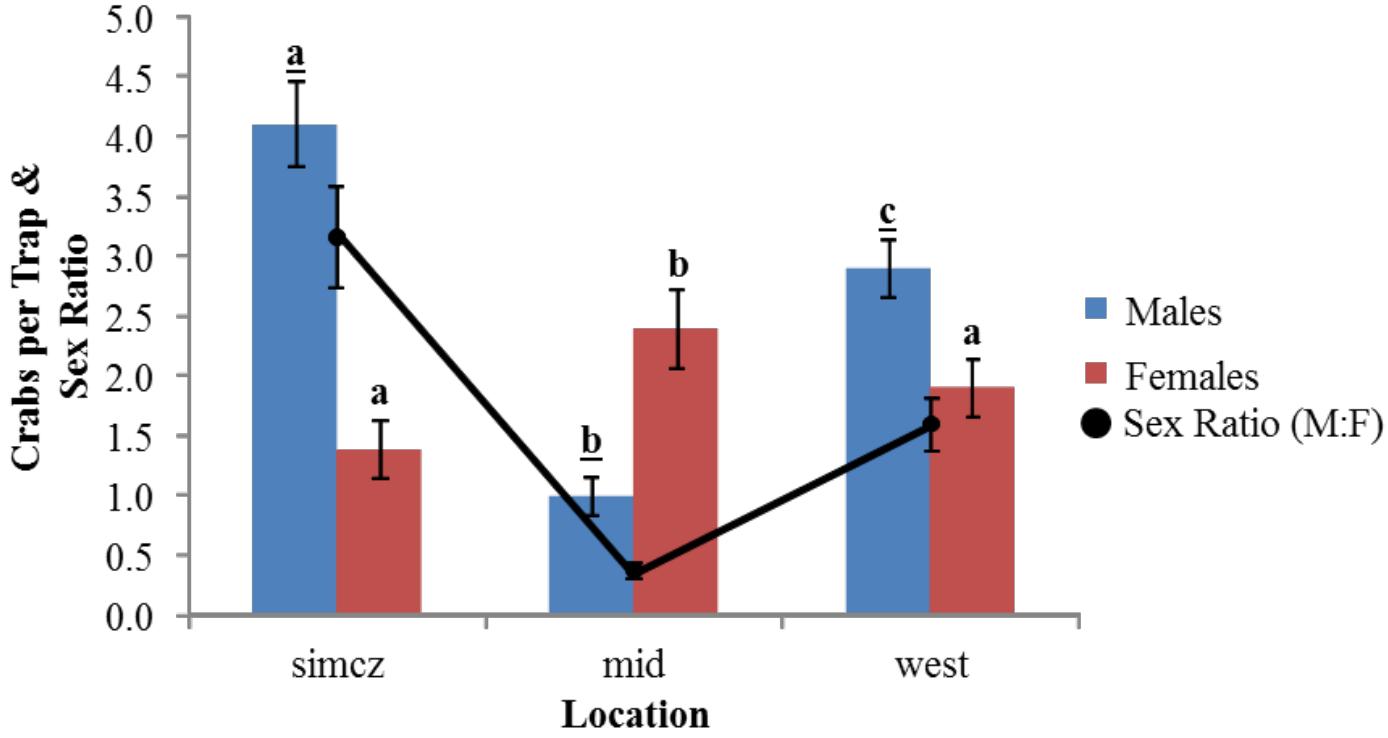

Figure 3. Abundance (± 1 SE) of male and female blue crabs captured and the sex ratio (M:F) (± 1 SE) in the SIMCZ, mid, and west areas of the bay, June-August 2012-2013. Letters above bars indicate significant differences within each dependent variable: lower-case=females, underlined lowercase=males. Bars with different letters are significantly different, P<0.05.

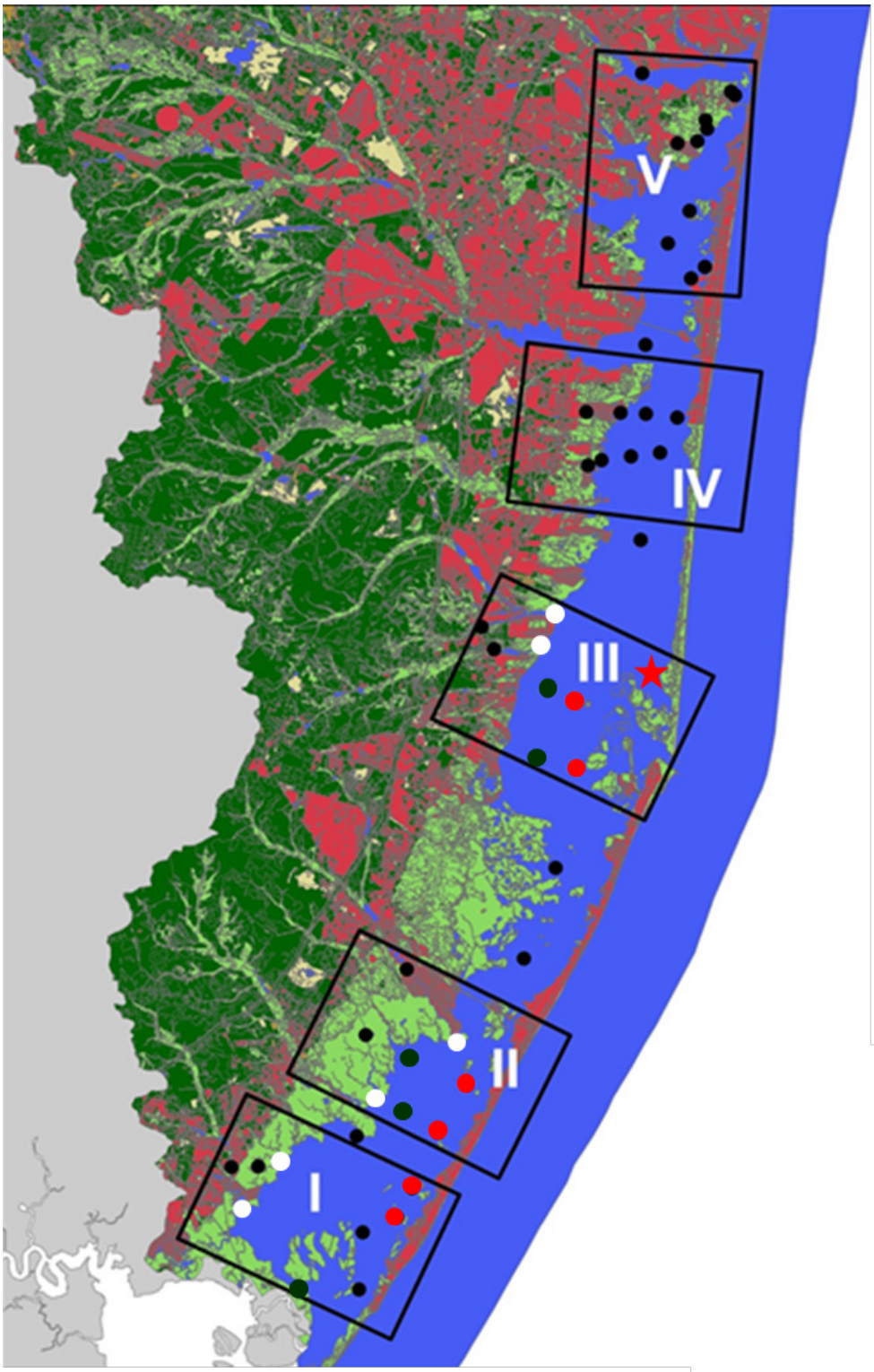

Figure 4. Map of Barnegat Bay including 5 sampling areas used to examine the influence of human urbanization on fish and crabs. The analysis in this report includes areas I-III. Dots inside each area are sampling sites: red dots=SAV, green dots=open bay, white dots=creek mouths. Black dots indicate sites not used in the analysis for this report. The red star indicates the SIMCZ.

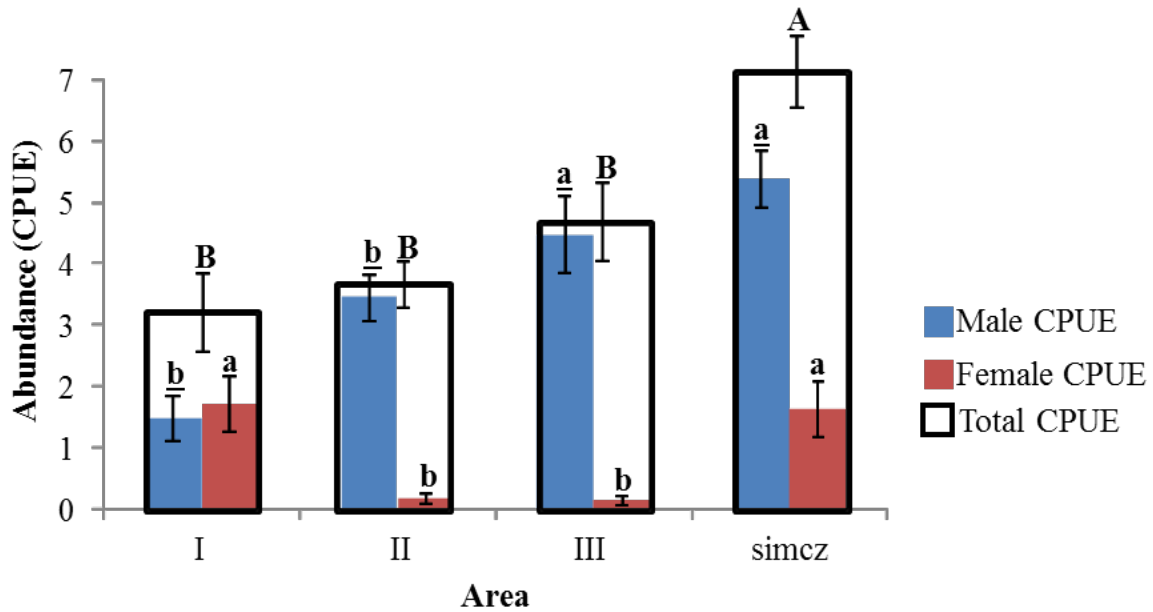

Figure 5. Average (± 1 SE) abundance (CPUE) of male, female and total blue crabs captured in SAV-dominated habitats along the western shore of Barnegat Bay including inside the SIMCZ, June-August 2012-2013. Letters above bars indicate significant differences relative to the SIMCZ within each dependent variable: lower-case=female cpue, underlined lowercase=male cpue, upper-case=total cpue. Bars with different letters are significantly different, P<0.05.

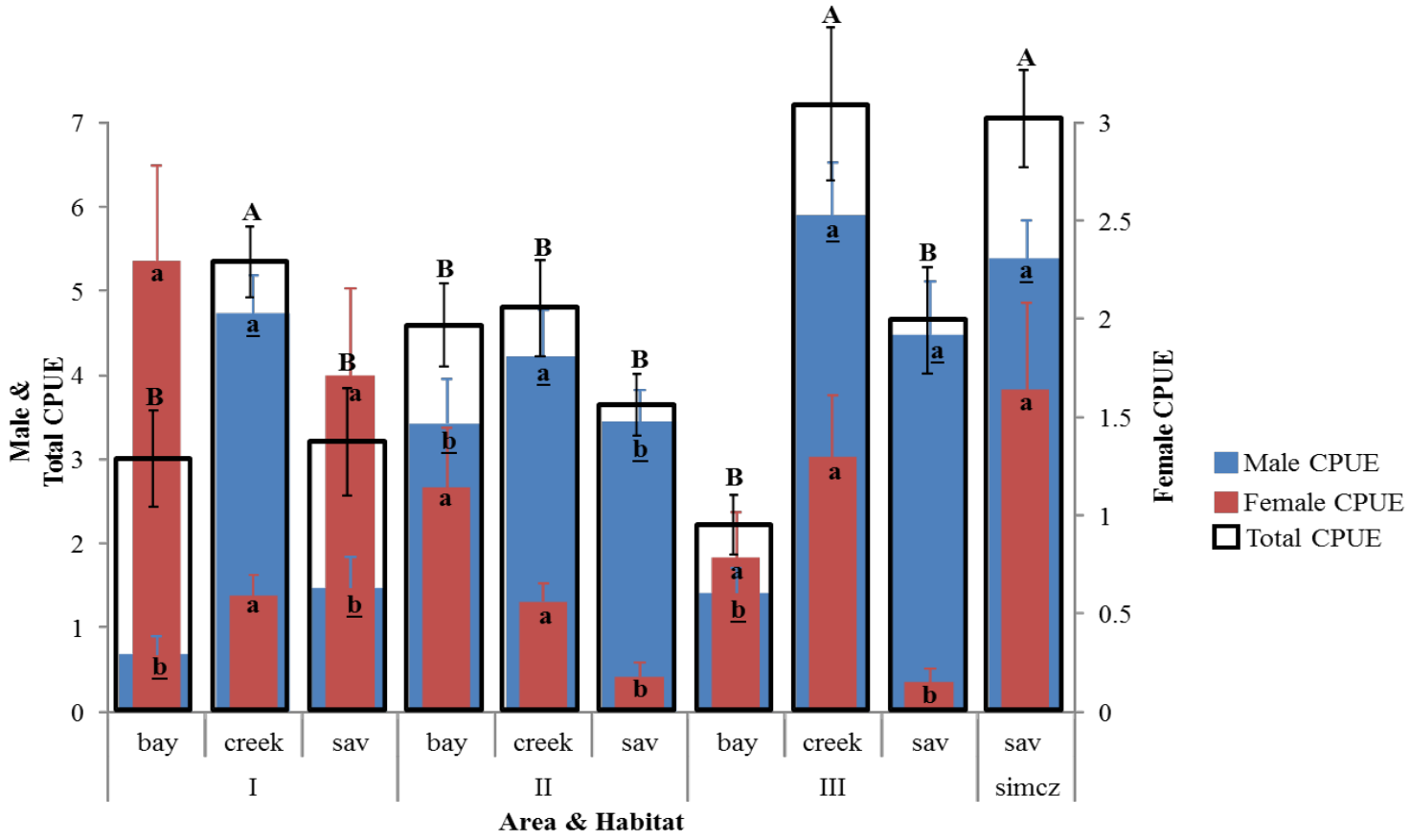

Figure 6. Average (± 1 SE) abundance (CPUE) of male, female and total blue crabs captured in bay, creek and sav habitats in Barnegat Bay including inside the SIMCZ, June-August 2012-2013. Letters indicate significant differences relative to the SIMCZ within each dependent variable: lower-case=female cpue, underlined lowercase=male cpue, upper-case=total cpue. Bars with different letters are significantly different, P<0.05.

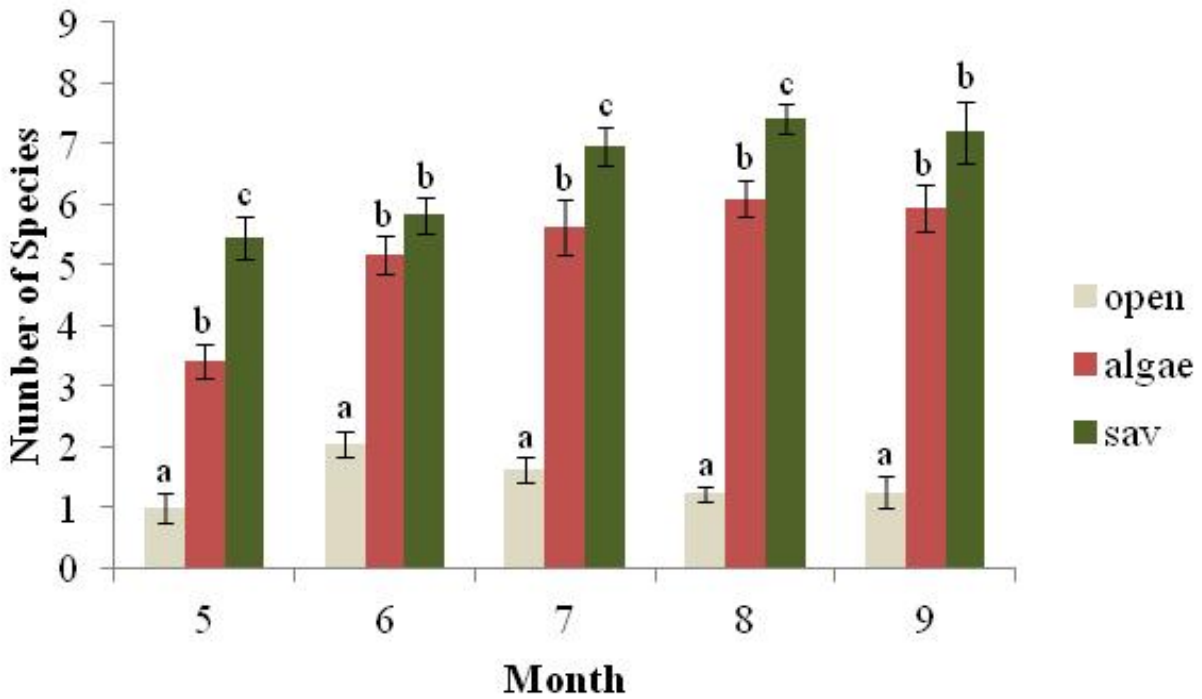

Figure 7. Monthly average (± 1 SE) number of species captured in throw traps in each habitat during the study period, May-September, 2012-2013. Different letters above the bars indicate statistical differences between habitats within each month, P<0.05.

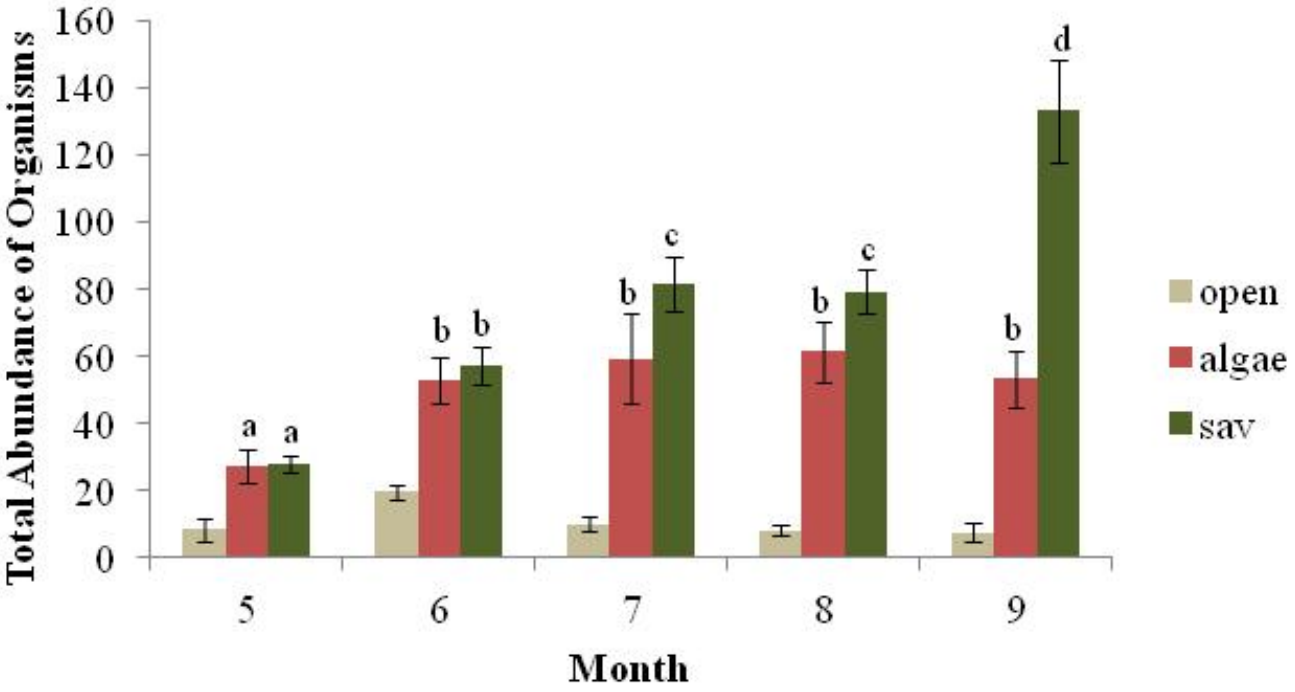

Figure 8. Monthly average (± 1 SE) abundance of all organisms captured in throw traps during the study period, May-September, 2012-2013. Different letters above the bars indicate statistical differences between months within each habitat, P<0.05.

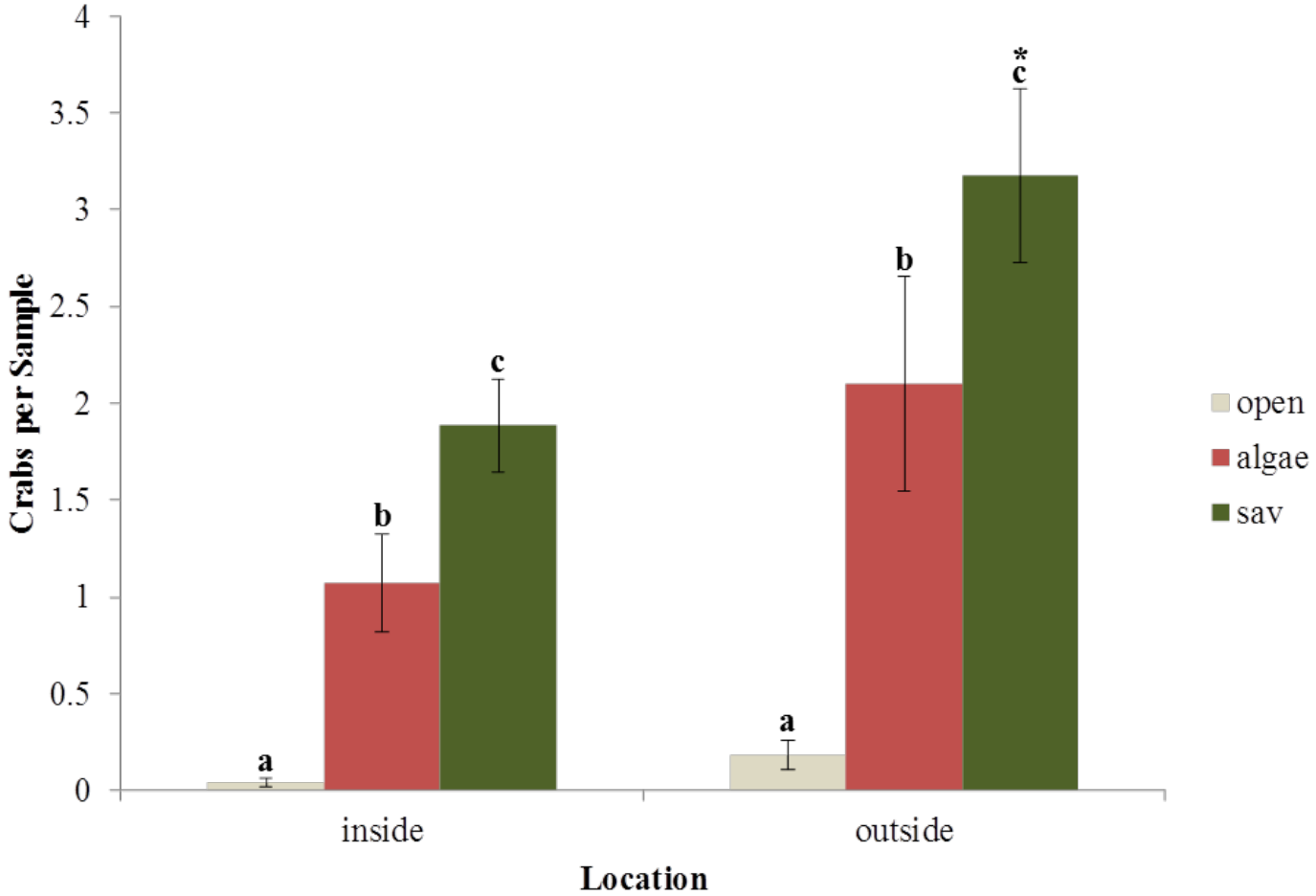

Figure 9. Abundance (± 1 SE) of blue crabs captured in throw traps in each habitat during the study period, May-September, 2012-2013. Different letters above the bars indicate statistical differences between habitats within each location, P<0.05. * indicates statistical differences within habitats between locations, P<0.05.

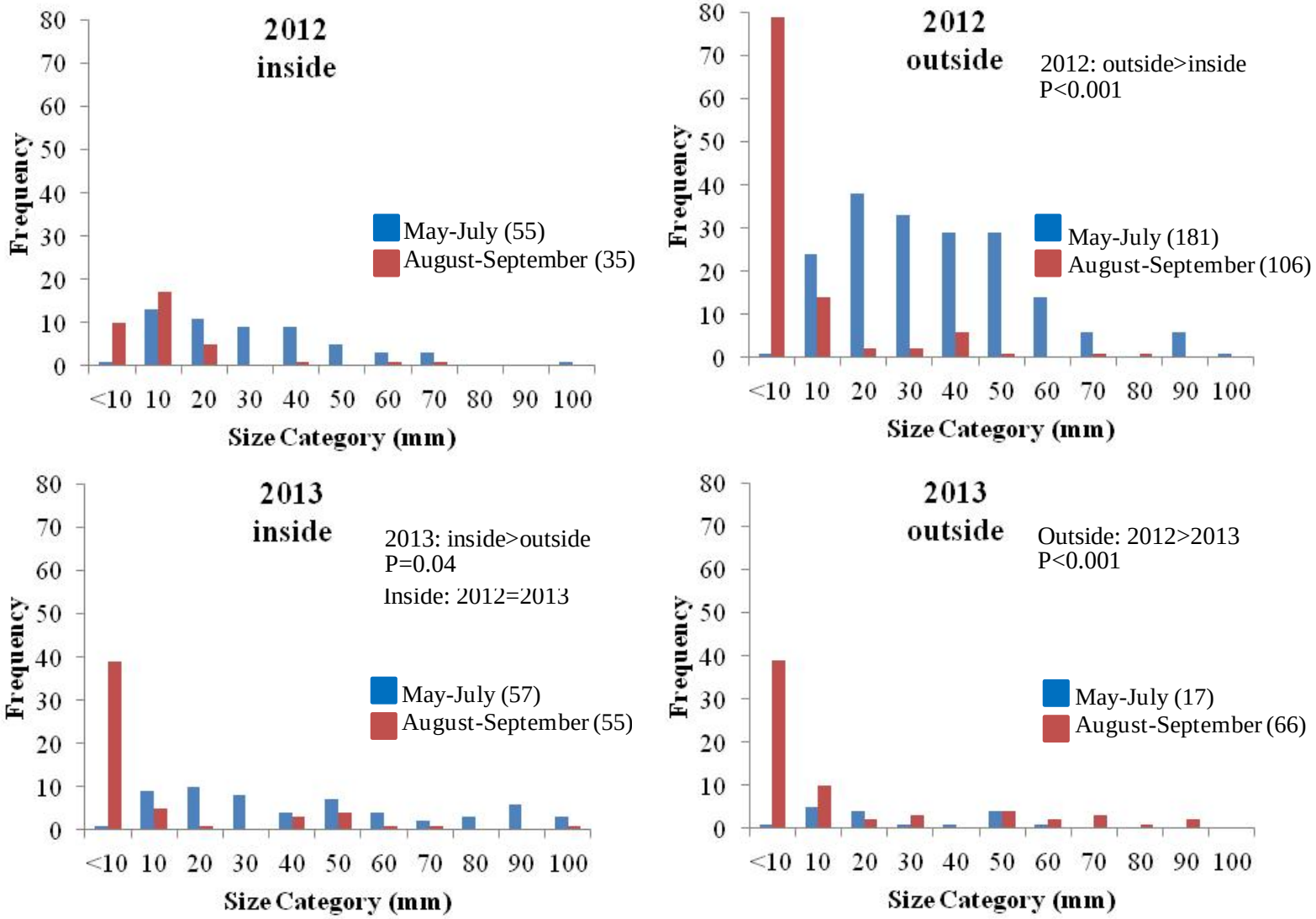

Figure 10. Annual size frequency distributions (10mm size increments) of blue crabs in each location during two time periods per year; May-July and August-September. Sample sizes are in parentheses.