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Spatial variation in fishery exploitation of mature female blue crabs (C. sapidus) in Chesapeake Bay

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Spatial variation in fishery exploitation of mature female blue crabs (*C. sapidus*) in Chesapeake Bay

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Abstract

From 2008 to 2012, the total U.S. commercial landings of blue crabs (*Callinectes sapidus* Rathbun, 1896) averaged over 173 million lbs. Chesapeake Bay and its tributaries are important contributors to this fishery, providing greater than 30% of national commercial landings annually. In Chesapeake Bay, *C. sapidus* exhibits a complex life cycle in which mated females migrate to the saline waters of the Bay mouth to spawn. During migration, females can traverse multiple management jurisdictions, complicating effective management of this important fishery. Sustained declines in harvest have led to management strategies focused on protecting the female spawning stock in an attempt to enhance recruitment back into the Bay. This study presents the results of a broad scale mark-recapture study (n=7,072) in 11 Chesapeake Bay subestuaries and one coastal embayment, designed to track female migration and quantify spatial variation in exploitation rates of mature female blue crabs. Tagging was conducted in fall 2014 (September and October), when most females have matured and begin to migrate to the spawning grounds, and in summer 2015 (July), when additional females mature and migrate to the spawning grounds. Approximately 8.1% of tagged females were recaptured within one year of release. Overall, the exploitation rate of the 2015 blue crab spawning stock in Chesapeake Bay was 10.5%; however exploitation varied widely among systems (4.0-28.5%). This estimate is below both the management target and threshold exploitation rates and the population grew in subsequent years, suggesting recruitment overfishing of blue crabs was not occurring in Chesapeake Bay at this time.

Introduction

Blue crabs, *Callinectes sapidus*, are broadly distributed throughout the coastal and estuarine waters of the western Atlantic Ocean and Gulf of Mexico (Rathbun 1896). Blue crabs are an important component in the community ecology of estuaries and nearshore habitats, playing a variety of roles in both Chesapeake Bay and other systems (Baird and Ulanowicz 1989; Hines et al. 1990; Silliman and Bertness 2002). For example, *C. sapidus* can have significant impacts on infaunal organisms in these systems, exerting top-down control on the abundance and community structure of marine worms and clams (Hines 1990). Predation by blue crabs may also serve as a natural control of invasive species: this species may be limiting invasive rapa whelk *Rapana venosa* populations in lower Chesapeake Bay (Harding 2003) and controlling invasive European green crab *Carcinus maenas* abundances along the East Coast of North America (deRivera et al. 2005). Blue crabs also support a commercially and recreationally important fishery and are prey for many species throughout their range (Guillory and Elliot 2001). In Chesapeake Bay, *C. sapidus* is a dominant component of both cobia *Rachycentron canadum* and striped bass *Morone saxatilis* diets (Arendt 2001, Walter III et al. 2003).

Blue crabs exhibit a complex life history involving the use of multiple marine and estuarine habitats. Clutch sizes generally range between 2-5 million eggs (Prager et al. 1990) and eggs hatch into zoea – the larval form – after 14 to 17 days (Tagatz 1968; Millikin and Williams 1984). Zoea are then transported out of the estuary to the continental shelf and eventually back to settlement habitats in estuaries by surface winds and currents (Epifanio 1995, Ogburn et al. 2012). Larval and postlarval stages require the high salinity of marine waters for successful development (Costlow and Bookhout 1959). Juvenile blue crabs inhabit the shallow tributaries of Chesapeake Bay (Hines 2007; Lipcius et al. 2007), taking advantage of structured habitats

throughout the estuary as they grow to maturity (Perkins-Visser et al. 1996; Hovel and Lipcius 2001, 2002). Females pair with a male immediately prior to a functional terminal molt, and following molting will mate while still soft while males protect the vulnerable, soft-shelled females until they harden post-copulation (Van Engel 1958). Males remain in the nursery waters of tributaries as adults but inseminated females undergo a long-distance migration to the saline spawning waters of the lower Bay, where they begin to produce broods of eggs (Aguilar et al. 2005, Hines et al. 2008). Transport of hatched zoea out of the Bay, and ultimately recruitment back into Chesapeake Bay, is dependent on mature female survival through this migration to the saline spawning grounds near the Bay mouth.

C. sapidus is a commercially and recreationally important fishery species. According to the National Marine Fisheries Service (NMFS), an average of 175.4 million lbs. of blue crab (hard, soft, and peeler) was landed by commercial fisherman domestically in the U.S. between 2008 and 2012 (NMFS 2014). In 2013 alone, blue crab landings accounted for about $195 million in commercial sales (NMFS 2014). Historically, the Chesapeake Bay harvest has made up about 90% of commercial *C. sapidus* landings in the Mid-Atlantic region (NMFS 1981, 1986). Female crabs are subject to fishing pressure throughout the distance of their migration – traversing long distances down-estuary – and this can impact spawning stock abundance. Over the past two decades, the overall abundance of blue crabs in Chesapeake Bay has dropped by about 70%, and that of the spawning stock has dropped by about 81% (Lipcius and Stockhausen 2002).

Population declines have shifted management efforts towards the protection of the female spawning stock. For example, recreational fishers are currently prohibited from taking mature females in Maryland, the winter dredge fishery targeting females has closed in Virginia, and

spawning sanctuaries have been implemented in the lower Bay. Further, declines have prompted increased research efforts in the region through collaborations among the Maryland Department of Natural Resources, Virginia Marine Fisheries Commission, and the Potomac River Fisheries Commission (PRFC), the three agencies that manage blue crabs in Chesapeake Bay. The Chesapeake Bay Stock Assessment Committee (CBSAC) brings together scientists and state representatives from Maryland (MD), Virginia (VA), and the PFRC to develop management advice for blue crabs and other species. The committee combines current scientific understanding of the biology and ecology of blue crabs with fishery-independent surveys and harvest data to assess the Chesapeake Bay blue crab stock.

Bay-wide assessments were conducted in 1997 (Rugolo et al. 1997), 2005 (Miller et al. 2005), and, most recently, 2011 (Miller et al. 2011). The most recent assessment recommended a target abundance of 215 million female spawning-age crabs, replacing the previous target of 200 million total spawning-age crabs. This change was reflective of the shift in the focus of management of the Chesapeake Bay blue crab stock towards protecting the female spawning stock. Further, female-specific exploitation rates were implemented to reduce the likelihood of recruitment overfishing; rates of fishing that reduce spawning stock biomass to levels that jeopardize future recruitment. The 2011 assessment established a minimum biomass threshold of 70 million female spawning-age crabs in the Bay and found a contemporaneous abundance of 190 million (Miller et al. 2011). The corresponding target and threshold exploitation figures were 25.5% and 34%, respectively (Miller et al. 2011).

The most recent CBSAC blue crab advisory report prior to this study (2014) reported that the stock of spawning-age female blue crabs in Chesapeake Bay (68.5 million individuals) was below the target threshold of 70 million and, as such, was depleted (i.e. below the minimum

threshold). However, despite the low abundance of spawning-age female blue crabs, juvenile crab abundance increased because of strong recruitment (presumably resulting from favorable environmental conditions). In 2014, CBSAC suggested protection of the mature female population as a long-term management strategy to promote their survival through spawning, allowing the population to replenish itself from exploitation and increase resilience to environmental disturbances (CBSAC 2014). CBSAC also recommended extending enforcement of the Virginia Blue Crab Sanctuary, a marine protected area in lower Chesapeake Bay, from seasonal to year-round enforcement to protect spawning females. The decrease in mature females observed in 2014 could limit subsequent recruitment and, ultimately, overall abundance in Chesapeake Bay. Annual reports from CBSAC track the long-term changes of the blue crab population and inform management decisions for recreational and commercial fishing.

Accurate estimation of annual exploitation throughout the Bay is a critical component of these reports which provide recommendations for fishery managers and identify research needs. Current exploitation figures are derived using estimates of harvest and exploitable spawning stock size (Miller et al. 2011). However, both estimates are uncertain and an independent estimation of the exploitation rate would prove valuable for comparison to the derivative figures calculated in such reports. Mark-recapture is a common method for estimating fishery exploitation, including in studies of blue crabs in Chesapeake Bay (Sharov et al. 2003, Lambert et al. 2006, Hewitt et al. 2007). The present study consists of a large-scale mark recapture project that quantifies fishery exploitation of mature female blue crabs in Chesapeake Bay and its tributaries. Exploitation was estimated for individual subestuaries, geographic regions, regulatory jurisdictions, and overall in Chesapeake Bay during female migration from nurseries to the

spawning grounds of the Bay mouth. Additionally, the efficacy of extending enforcement of the Virginia Blue Crab Sanctuary was assessed.

Methods

Study sites

A large-scale, fishery-dependent mark-recapture study was conducted to quantify fishery exploitation of mature female blue crabs in 15 sites (12 individual systems, 3 repeated sites) throughout Chesapeake Bay. These systems are distributed throughout Chesapeake Bay – including both the Eastern and Western shores – and represent a broad range of coastal habitats (Figure 1; Table 1).

Collection & Tagging

Adult female blue crabs were caught in coordination with local commercial fishers. In each subestuary, a target number of 500 individuals was tagged. The carapace width (CW) of each crab was measured and individuals were assessed for limb loss and relative health prior to tagging. Only recently mated females that showed no visible signs of disease or injury were selected for tagging; those missing both chelipeds or both swimming legs, missing more than three total limbs, or showing visible signs of disease or injury were not tagged. Tags were 1" x 2" white vinyl rounded-rectangles (Figure 2) that were attached to the dorsal carapace with 0.024" diameter annealed stainless steel wire (Wickwire Warehouse Inc., Philadelphia, PA, USA) wound around the lateral spines (Figure 3). If a crab did not appear in good health post-tagging, the tag was removed and the individual was released. Each tag had a unique identification number and listed contact information for the Smithsonian Environmental

Research Center's (SERC) 'blue crab hotline' and tag reporting website (Figure 2). Tags were assigned either standard ($5) or high ($50) reward values and high value tags were assigned randomly to individuals. Reward amounts were clearly visible on tags such that high value tags were easily distinguishable from standard value tags. Prior field and laboratory experiments have demonstrated negligible mechanical tag loss (loss probability=0.00067 d^{-1}), and crabs that did lose tags did so after an average of 31.4 days (Hines et al. unpublished data). Additionally, no post-handling mortality was observed for crabs tagged in this manner and held in tanks for >1 month if they were released within 25 minutes of capture (Hines et al. unpublished data).

Tagging occurred Bay-wide in fall 2014 (September and October) when the majority of females mature and migrate to spawning grounds in lower Chesapeake Bay and focused on lower Bay subestuaries in summer 2015 (July) when additional females mature and migrate to the spawning grounds. By targeting mature female blue crabs at the beginning of their migration to spawning waters, this study focused on exploitation of the 2015 blue crab spawning stock in Chesapeake Bay.

Recapture data were obtained either electronically via web form or via telephone. Captors were asked to provide their name, address, and contact information for receipt of reward. Each captor was then sent an invoice for their reward, a map on which they were asked to mark the capture location of the crab(s), a survey that asked for information on capture gear (pot, trotline, handline, etc.), fishery sector (commercial or recreational), date of capture, depth, location (GPS coordinates if known), and tag number(s), and a prepaid self-addressed envelope with which to return the documents and tags if they were removed from the crab. The reverse side of the tags also requested captors record this information upon capture (Figure 2). If coordinates were not provided for the recapture location, either the marked map or a written description of the location

was used to approximate the recapture location. Recapture reports for which no recapture location information was given (no coordinates, no marked map, and no approximate location) were included in estimates of exploitation, but not in spatial analyses. The number of days at large, defined as the time between release and fishery recapture, was calculated for each crab for which recapture date was reported.

Reporting Rates & Exploitation

Reporting rate (λ) was estimated as the rate of standard value tag recapture relative to the rate of high value tag recapture (Eq. 1). High value tags were clearly marked with “$50” on the outward-facing side of the tag and were easily distinguishable from standard value tags. All tags also had “Reward” marked on the visible side of the tag. Tag return rate was calculated as the number of tags returned over the number of tags released; however, this figure underestimates the actual recapture rate if tags are recaptured but not reported. The standard tag reporting rate was estimated as the return rate of standard value ($5) tags relative to the return the return rate of high value ($50) tags via the following equation:

(*Eq. 1*) $$\lambda = (R_s/N_s)/(R_r/N_r)$$

where R_s is the number of standard value tags returned, N_s is the number of standard value tags released, R_r is the number of high value tags returned, and N_r is the number of high value tags released. This equation assumes that the reporting rate of high value tags is 1 (all high value tags are reported) and uses that rate to adjust for possible underreporting of standard value tags (Pollock et al. 2001). Previous studies in Chesapeake Bay observed no difference in reporting rate of $50 and $100 tags, suggesting $50 was sufficient to achieve 100% reporting of high value tags (Hines et al. unpublished data). If the calculated reporting rate for a system was >1, a 100%

reporting rate (λ = 1) was assumed. The reporting rate was then used to determine the exploitation rate (μ) as shown in the following equation:

(*Eq. 2*) $$\mu = [(R_s/\lambda) + R_r]/(N_s + N_r)$$

These equations were used to calculate exploitation by season, by system, by jurisdiction, and by region, as described in subsequent sections. Recaptures for which no location was reported were included in both system-specific and overall exploitation calculations but removed from spatial analyses as specified below.

A single exploitation rate was also calculated for the sampled coastal embayment and tributaries of Chesapeake Bay combined to estimate the Bay-wide fishery exploitation of the 2015 blue crab spawning stock. The simplest method for estimating exploitation, this calculation pooled the recaptures from all releases. All recaptures, regardless of missing recapture location or date, were used in this calculation. This calculation did not account for natural mortality (overwintering and total natural), regional variation, or season and thus represents an overall estimate of exploitation; however, these variables were taken into consideration in subsequent calculation methods.

Spatial Analyses

All projections and spatial analyses were conducted using ArcMAP 10.5 (ESRI Inc. Redlands, CA, USA). Recapture coordinates were plotted to demonstrate the overall pattern of female migration from nursery habitats to the spawning grounds at the mouth of the Chesapeake Bay. The number of days between release and subsequent recapture was used to evaluate timing and route of migration. Recaptures for which no recapture date was reported were removed from these projections.

Seasonal Exploitation

Exploitation was calculated by season to determine how fishery exploitation of the 2015 blue crab spawning stock varied temporally. Recaptures were pooled as follows for seasonal calculations: fall recaptures of fall-released individuals, spring/summer (post-overwintering) recaptures of fall-released individuals, and recaptures of summer-released individuals. Fall exploitation of fall-released individuals was calculated by combining all fall (September-December) recaptures of crabs from fall releases. Mortality and tag loss were not included in this calculation. Spring/summer exploitation of fall-released female blue crabs was calculated by adjusting for mortality and tag loss (*Eq. 3-5*). Natural mortality for blue crabs is uncertain, with previous studies suggesting the use of a range of values in assessment models (Hewitt et al. 2007). The number of living tagged crabs was adjusted for three different mortality rates prior to exploitation calculations in the present study: M=0 (no mortality), the 2015 overwintering mortality rate of mature female blue crabs in Chesapeake Bay (M_{ow}=19.25%, CBSAC 2015), and M=0.9 (Miller et al. 2005). Annual natural mortality (M) was scaled to accurately reflect the average time at large (T), or the average date of all spring recaptures of fall-released crabs minus the average fall release date (*Eq. 5*)

(*Eq. 3*)

$$\mu_{M=0} = \frac{\left(\frac{R_{s(summer)}}{\lambda_{(summer)}}\right)+R_{r(summer)}}{\left[N-\left(\frac{R_{s(fall)}}{\lambda_{(fall)}}+R_{r(fall)}\right)\right](1-.00067)^{T}}$$

(*Eq. 4*)

$$\mu_{Mow=19.25\%} = \frac{\left(\frac{R_{s(summer)}}{\lambda_{(summer)}}\right)+R_{r(summer)}}{\left[N-\left(\frac{R_{s(fall)}}{\lambda_{(fall)}}+R_{r(fall)}\right)\right](1-.00067)^{T}(1-.1925)}$$

(*Eq. 5*) $$\mu_{M=0.9} = \frac{\left(\frac{R_{s(summer)}}{\lambda_{(summer)}}\right)+R_{r(summer)}}{[N-(\frac{R_{s(fall)}}{\lambda_{(fall)}}+R_{r(fall)})(1-.00067)^{T}]e^{-0.9(\frac{T}{365})}}$$

After adjustment for natural mortality, N was further adjusted for tag loss over the same time period (loss probability=0.00067 d^{-1}). Tag loss represented the proportion of crabs that lost their tag during the average time at large. Exploitation of summer-released crabs was calculated by combining all recaptures of crabs from summer (July) releases. Mortality and tag loss were not included in this calculation. Recaptures for which no recapture date was reported were removed from all seasonal exploitation calculations.

Individual Subestuaries

To assess how fishery exploitation varies spatially throughout Chesapeake Bay, system-specific estimates of exploitation were calculated for each site in which female blue crabs were tagged and released. System-specific exploitation was calculated using all recaptures from an individual release, regardless of recapture date. Annual exploitation rates were calculated separately for each year in the three subestuaries where tagging was repeated in summer 2015 (Bradford Bay, Pungoteague Creek, and the York River). All recaptures, regardless of missing recapture location or date, were used in individual subestuary exploitation calculations.

Jurisdictional & Regional Exploitation

To evaluate potential differences in exploitation across management areas, exploitation rates were calculated for each of the three jurisdictions in Chesapeake Bay: MD, the Potomac River (PR), and VA. The exploitation of MD blue crabs was calculated by pooling recaptures from all

MD subestuary releases, the exploitation of Potomac River blue crabs was calculated using only the Potomac River release, and the exploitation of VA blue crabs was calculated by pooling recaptures from all VA subestuary releases. Summer 2015 releases were not included in these calculations because tagging was only conducted in VA. Recaptures for which no recapture date was reported were removed from seasonal calculations. For recaptures in which no recapture location was given, the fisher's state of residence was used to assign the catch to the appropriate jurisdiction.

To determine where crabs from each management jurisdiction (MD, Potomac River, and VA) are exploited, the proportion of recaptures reported within each jurisdiction was calculated. A spatial query was used to select all recaptures of crabs from a given jurisdiction, and the proportion of selected recaptures within each management area was calculated (i.e. of MD-released crabs that were recaptured, x% were caught in MD, y% were caught in the Potomac River, and z% were caught in VA). The tidal mainstem of the Potomac River is managed independently of tributaries on the northern and southern shores of the river, which are managed by MD and VA, respectively (Figure 4, PRFC). For a relatively small number of recaptures (n = 14), no recapture location was given so the fisher's state of residence was used as a proxy to assign the catch to the appropriate jurisdiction. Crabs released in Bradford Bay were excluded from this analysis because crabs from this coastal embayment were extremely unlikely to travel into neighboring jurisdictions given the geography of the Delmarva Peninsula.

Release sites were separated by region to compare exploitation of crabs originating in upper and lower Chesapeake Bay. Calculation of the overall exploitation of crabs from upper Bay tributaries included all releases up estuary of Cove Point (38.3857° N, 76.3812° W), and lower Bay tributaries included all releases down estuary of Cove Point. Bradford Bay was not

included because it is not in Chesapeake Bay proper. These calculations were only conducted on data from fall releases, as upper Bay sites were not included in summer tagging. All recaptures, regardless of missing recapture location or date, were used in these calculations.

Spawning Sanctuary Analyses

In 2000, VMRC created a spawning sanctuary for blue crabs in lower Chesapeake Bay. Early studies determined the established sanctuary protected an estimated 22% of the spawning stock but did not meet minimum recommendations of contemporary stock assessments, suggesting substantial expansion of the sanctuary (Seitz et al. 2001). Recent advisory reports have suggested similar action, establishing a year-round spawning sanctuary in lower Chesapeake Bay to protect the female spawning stock from fishery exploitation (CBSAC 2014, 2015, 2016). The present sanctuary is made up of five zones with variable closure windows that start in early May and open in mid-September (Figure 5). To assess the potential efficacy of a year-round sanctuary, we recalculated the exploitation rate after exclusion of all recaptures within the area of the current spawning sanctuary as defined by the Code of VA (4VAC20-752-10 et seq). This calculation pooled the recaptures from all releases (except Bradford Bay, the coastal embayment) to estimate Bay-wide exploitation after extending the current sanctuary which, in its present form, implements a northward rolling closure beginning in early May and lasts until mid-September (Figure 5). A second evaluation queried recaptures in the Bay mainstem, below the MD-VA border to approximate crabs that had successfully migrated to suitable spawning areas. Those that were recaptured within their subestuary of origin were not included in this query. The proportion of those recaptures within the current sanctuary boundary was then calculated to estimate how capture of migrated mature females might differ if year-long sanctuary

enforcement was implemented. For both evaluations, recaptures for which no recapture location was reported were removed. Additionally, recaptured crabs whose location was ambiguous and could have been either inside or outside of the sanctuary were not included to minimize potential bias.

Results

A total of 7,072 individual mature female blue crabs were tagged and released in subestuaries of Chesapeake Bay during this study (Table 1). Of these, a total of 6,573 were used in overall analyses as some individuals were excluded for various reasons: (1) all released individuals from the Little Choptank River release were removed due to low fisher participation ($\lambda \approx 0$), (2) six recaptures (three standard and three high value) were recaptured in the winter oyster fishery, and (3) five tags were reported multiple times. After exclusions, the total number of tagged crabs used for analyses was 6,573 with 563 individuals (R_s=529, R_r=34) recaptured and reported (8.6%). Of those that indicated fishing sector, 98.4% were caught by commercial fishermen (n = 488) with the remaining 1.6% caught/reported by the recreational sector (n=8). Overall, Bay-wide reporting rate was 80.8% resulting in an adjusted exploitation rate (μ/λ) of 10.5% for the 2015 Chesapeake Bay blue crab spawning stock (Table 2).

Spatial Analyses

With increased time at large, tagged females were generally captured further from their initial release site and nearer spawning waters near the Bay mouth (Figure 6). The number of days at large for tagged individuals ranged from 0 days (captured on the same day of release), to over a year (up to 410 days). Five recaptures did not include a date of recapture and thus were

not included in the projection. Three additional recaptures did not include a location or GPS coordinate and were also excluded from the projection.

Seasonal Exploitation

In total 5,190 female blue crabs were tagged in the fall of 2014 and 1,383 were tagged in the summer of 2015. The fall exploitation rate of fall-released crabs was 8.0% and the spring/summer exploitation rate (assuming M=0) was 2.1% (Table 3). A total of 90 summer-released individuals were recaptured. The exploitation of summer-released crabs was 12.5% (Table 3).

The difference between the average spring recapture date and average release date of fall-released crabs (T) was 220 days. After adjustment for natural mortality and tag loss for 220 days (*Eq. 5*), the spring/summer exploitation of fall-released crabs increased to 3.1%. By comparison, adjustment for the 2015 overwintering mortality rate of mature female blue crabs in Chesapeake Bay (*Eq.* 4) resulted in a spring/summer exploitation of fall-released crabs of 2.6% (Table 3). Six crabs were captured during the assumed overwintering period (December – March). Five of these were caught in the oyster fishery and one was caught in a commercial crab pot (late March). Those caught in the oyster fishery were not included in calculation of exploitation rate. Five recapture reports (two from the Chester River release, two from the James River release, and one from the fall Bradford Bay release) did not include a recapture date and were also removed from analyses.

Individual Subestuaries

System-specific estimates of exploitation were calculated for sites in which female blue crabs were tagged and released (Table 2). Reporting rates ranged from 20.6% (summer York River release) to over 200% (Rhode River). A reporting rate of 100% was assumed for all releases for which calculated reporting rates were in excess of 100%. The figures are denoted by an asterisk (*) in subsequent sections. Exploitation rates ranged from 4.0% (Rappahannock River) to as high as 28.5% (summer York River release). Reporting and exploitation rates could not be calculated for the Nanticoke River, York River (fall), and Pungoteague Creek (summer) releases, as no high value tags were recaptured.

Jurisdictional & Regional Exploitation

Overall exploitation rates were calculated for each of the three separately managed areas in Chesapeake Bay: MD = 8.6% (λ = 100%*), Potomac River = 18.2% (λ = 76.9%), VA = 12.2% (λ = 69.8%). To evaluate where separately managed crabs are harvested, exploitation was calculated separately by management area; the percentage of recaptures that occurred in each was used to evaluate where crabs are being exploited (Figure 7). Of the 197 recaptured MD-released crabs, 75.6% were recaptured in MD and 23.4% were recaptured in VA. Of the 62 recaptured Potomac River-released crabs, 77.4% were recaptured in the Potomac River and 19.4% were recaptured in VA. All 206 recaptures of VA-released crabs occurred in VA waters. Additionally, mature female crabs originating in upper Bay subestuaries were exploited at a higher rate than those from lower Bay subestuaries; the exploitation rate of mature female blue crabs from upper Bay subestuaries was 12.1% and that of those from lower Bay subestuaries was 9.4% (Table 4).

Spawning Sanctuary Analyses

The potential efficacy of extending the current Virginia Blue Crab Sanctuary to year-round closure was evaluated. Six recaptures did not include a location of recapture or GPS coordinate. After removing these and recaptures of Bradford Bay-released individuals (fall and spring), a total of 463 crabs were recaptured (R_s = 435, R_r= 28) and the overall exploitation was 10.1% (λ=80.5%). A total of 22 crabs were recaptured within the defined sanctuary (Figure 8). After removing these, a total of 441 crabs were recaptured (R_s =414, R_r = 27). The overall exploitation rate of mature female blue crabs after exclusion of recaptures within the current sanctuary to simulate year-round enforcement of the current spawning sanctuary was about 9.8% (λ = 79.4%), a reduction of 0.3%. A total of 130 crabs were recaptured in defined suitable spawning areas. Removal of recaptures within the current sanctuary (22 total) reduced capture of mature female crabs that successfully migrated to spawning areas by about 17%.

Discussion

This study used a large-scale, mark-recapture experiment to quantify fishery exploitation rates of mature female blue crabs within Chesapeake Bay. Female blue crabs generally migrated mouthward in fall, with some additional females migrating toward spawning grounds at the Bay mouth in spring/summer. Fishery exploitation of migrating crabs in individual Chesapeake Bay tributaries varied widely, ranging from 4.0% to 28.5% while the overall fishery exploitation rate of the 2015 blue crab spawning stock in Chesapeake Bay was 10.5%. Of the three managed jurisdictions, crabs tagged in the Potomac River were most heavily exploited, those tagged in MD were least exploited, and sizeable proportions of both stocks were recaptured in VA waters, further demonstrating migration toward the Bay mouth. Extension of the current Virginia Blue

Crab Sanctuary to year-round enforcement could reduce mature female exploitation in lower Bay spawning areas by up to 17%. These results provide independent estimates of fishery exploitation at the individual system, region, jurisdictional, and overall system levels and evaluate proposed modification of an existing marine protected area. As such, these figures should be considered in the management of mature female blue crabs in Chesapeake Bay. The results reported here are subject to change, as tags reported following this draft would affect calculations.

In total, 7,072 mature female blue crabs were tagged in 15 releases in 11 separate subestuaries and one coastal embayment and reporting rates were used to estimate exploitation. The overall estimated reporting rate of crabs was 80.8% but varied substantially among systems. For example, low participation in the Little Choptank River may have resulted from local closure to commercial oyster harvest and resulting mistrust of management and research efforts. Conversely, reporting rates in the Rhode River were 100%, likely a result of years of collaborations with local watermen in this system. In total, 563 crabs (about 8.6%) were recaptured throughout the course of the study. Previous research using similar tagging methodology noted that recapture rates varied annually, ranging from 4.3% to 17.7% (Aguilar et al. 2005). The recapture rate of this study (8.6%) fits within that range.

Most recaptures came from commercial fishers, a result consistent with previous tagging studies on adult female blue crabs in Chesapeake Bay (Lambert et al. 2006). Historically, recreational harvest of blue crabs is only 8% of total Bay-wide commercial harvest (Ashford and Jones 2003). Our estimate of recreational harvest of mature females (1.6%) was substantially lower than previous estimates. Changes in regulations since 2003 likely explain much of this difference; MD currently prohibits recreational harvest of female crabs and VA limits harvest of

sponge – or egg-bearing – crabs. These regulations, which were not in place when previous estimates of recreational harvest were calculated, could account for the relatively low observed recreational harvest of mature females in the present study.

The overall Bay-wide exploitation rate of the 2015 blue crab spawning stock was 10.5%. CBSAC estimated that female exploitation was 17% in 2014 and 15% in 2015 (CBSAC 2016). CBSAC estimates the exploitation fraction of female crabs as the total number harvested divided by the estimated abundance of females that will recruit to the fishery during the coming year. The total harvest of female crabs includes soft shell and peeler crabs, in addition to mature females. The figures reported here represent exploitation of mature females only and thus cannot be directly compared. CBSAC also groups harvest by year whereas our study looks at exploitation of a single spawning stock, which includes harvest in fall 2014 and spring and summer 2015. Additionally, our 10.5% estimate of spawning stock exploitation does not take natural mortality, regional variation, or season into account. Attempts were made in subsequent sections to address these factors but this method is valuable because it is easily calculated, it assigns a single exploitation rate to the entire Bay, and it incorporates all of the recapture data.

Methodology

Exploitation estimates using high-reward tagging are dependent on the assumption that the high value reward is high enough that 100% of high value tags are reported (Pollock et al. 2001). Previous studies conducted by SERC that used both \$50 and \$100 high-value reward tags indicated that \$50 was a sufficient reward to achieve a reporting rate of 1 (Hines et al. unpublished data). Pollock et al. (2001) note that problems can arise in high-reward tagging studies when tag returns are not independent; a fisher is not inclined to report a single tag but

will report with the cumulative incentive of multiple tags. However, this problem is minimized by tagging in a large number of locations (Pollock et al. 2001). The large spread of releases in the present study likely mitigates this issue for overall, jurisdictional, and regional exploitation estimates but could play a role in individual systems, where fishers were more likely to encounter multiple tagged individuals.

Small changes in the number of high value recaptures can greatly alter estimated exploitation rates, and likely affected recapture rates in individual subestuaries where sample size is much smaller than larger, pooled regions. A smaller high value recapture rate relative to standard value recapture rate can inflate the reporting rate to over 100%. Conversely, a larger high value recapture rate relative to standard value recapture rate can greatly decrease the estimated reporting rate. For example, if we assume that about 11% of high value tags are recaptured – the estimate from the present study – then less than three high value recaptures would be expected on average ($N_r = 25$). Variation in either direction, even by one recapture, affects calculated reporting rate (*Eq. 1*) and subsequently, the estimated exploitation rate. These effects are lessened in Bay-wide and jurisdictional scales (except the Potomac River), where the total number of high value tags released is greater than that in individual subestuaries and thus recapture rates are not as strongly affected by such variation.

Spatial Analyses

Mature female blue crabs generally demonstrated mouthward, down-estuary migration following tagging (Figure 7). This pattern mirrors that seen in previous studies, wherein mature females migrate to more saline waters in the lower estuary (Van Engel 1958, Millikin and Williams 1984, Aguilar et al. 2005). Most recaptures occurred within one year of tagging, with

only one occurring after 365 days (410 days at large). Recaptures were primarily in Chesapeake Bay proper and along the Delmarva Peninsula (Figure 7). One crab was recaptured in Croatan Sound, NC after 278 days at large; however, this recapture is not shown in the projection to improve the resolution for the other recapture points. Most recapture reports (98.9%) included GPS coordinates or a location name such that a coordinate could be found for mapping purposes. Many recaptures had similar or identical locations listed (i.e. Bradford Bay, Burton's Bay) and thus appear in very similar or the same location in the projection. Individual coordinates for each recapture would be preferred but were not necessary for general migration analysis.

Seasonal Exploitation

Overall, pooled exploitation of summer-released crabs was higher than exploitation of fall-released crabs for all three estimates of non-fishery mortality (M=0, M=0.9, M_{ow}=19.25%), suggesting higher fishing pressure on the Chesapeake Bay spawning stock in the summer. However, pooled exploitation of fall-released crabs at the three repeated sites (York River, Pungoteague Creek, and Bradford Bay) was about 13.5%, greater than the exploitation rate of the summer releases (12.5%). Exploitation could not be calculated for the fall York River release nor the summer Pungoteague Creek release due to lack of high value recaptures. Thus, exploitation of the fall release could not be compared to exploitation of the summer release for those individual systems. Exploitation of fall-released females was higher than that of summer-released females in Bradford Bay, the only site tagged in both seasons with high value recaptures from both releases. Previous tagging studies in the Potomac River between 2001 and 2009 suggests that female exploitation peaks in September and October, with landings in areas closer to the river mouth peaking later than those in the upper river (Johnson and Aguilar unpublished

data). The pattern in landings seen in Potomac River is consistent with the life history of blue crabs in Chesapeake Bay; most female migration toward the Bay mouth occurs in fall so large numbers of females are moving mouthward throughout the season. Over 20% of recaptures of fall-released females in the present study occurred in 2015, following overwintering. The majority of these recaptures occurred down estuary, nearer the Bay mouth than the point of release.

The average time at large of fall-released females recaptured in spring was used to estimate the length of natural mortality factored into exploitation calculations. This period was used for convenience but could have inflated exploitation estimates, as it could have been influenced by outliers such as the single recapture that occurred after 400 days at large, over 100 days later than the next longest time at large. Removing this point from calculations does not dramatically reduce either natural or overwintering mortality estimates of spring exploitation of fall-released crabs; adjusted exploitation rates are 3.0% and 4.1% for $M=0.9$ and M_{ow} = 19.25%, respectively. Seasonal exploitation rates could not be calculated for individual subestuary releases because high values tags were not recaptured following overwintering for eight of the eleven fall releases.

Individual Subestuaries

Fishery exploitation of mature female blue crabs varied substantially among individual subestuaries in Chesapeake Bay (Table 2). There were no clear spatial patterns for exploitation, and the mean exploitation rate was 15.0%. System-specific exploitation rates could prove valuable in future management that aims to protect spawning stock using spatial management. The highest exploitation rate was observed in the site with the lowest estimated reporting rate of

standard tags (summer York River release). A larger proportion of high value tags was recaptured relative to the proportion of standard value recaptures, yielding a low reporting rate and ultimately a large adjustment of exploitation. Exploitation could not be calculated for three releases – the Nanticoke River, fall York River, and summer Pungoteague Creek releases – because high value tags were not recaptured from these locations, precluding adjustment for potential underreporting. The numbers of reported standard value recaptures in these systems (6, 5, and 4, respectively) were also the three lowest such figures for all releases. Recaptures from individual subestuaries were not calculated seasonally for fall releases because doing so required recapture of high value tags in both fall and the following spring. This only occurred for the James River release, for which one high value tag was reported in fall and three were reported the following spring. Further investigation into seasonal variation in fishery exploitation in individual subestuaries would require higher volumes of tags per individual subestuary to increase likelihood of high value recaptures in all seasons. Bradford Bay was the only site tagged in both fall and summer for which exploitation could be estimated for each season, as high value tags were not recaptured for either the fall York River release or the summer Pungoteague Creek release.

The exploitation of fall-released Bradford Bay crabs (16.7%) was higher than that of those released in the spring (10.7%). Estimated reporting rates were 52.1% and 100%* for fall and spring respectively. The large disparity in reporting rate between these releases could account for the difference in estimated exploitation rates. For example, four high value tags were recaptured from the fall release and two were recaptured from the summer release in Bradford Bay, yielding the above dissimilar reporting rates. If the reporting rate of the fall release was adjusted to 100% (two more high value recaptures), the most conservative estimate because it

assumes all recaptured standard value tags were reported, the estimated exploitation rate changes to 9.1%, closer to the 10.7% observed in the spring than the original 16.7% fall estimate. Similar patterns with slightly elevated or depressed high value recaptures could have impacted exploitation estimates in other subestuaries, resulting in the large range of observed exploitation rates throughout the Bay, although reporting rates for all but two releases were greater than 50%. If robust estimates of reporting and exploitation rates are desired for individual subestuaries of Chesapeake Bay, larger numbers of tagged crabs should be released in each area.

Jurisdictional & Regional Exploitation

The Potomac River spawning stock was exploited at the highest rate of the three jurisdictions. This result was consistent across all mortality rates. The exploitation of the Potomac River stock was also among the highest individual subestuary estimates, exceeded only by the fall Pungoteague Creek and summer York River releases. CBSAC (2014-2016) recommends consideration for additional management measures or a spawning sanctuary in both MD and the Potomac River to complement the present Virginia Blue Crab Sanctuary to protect the spawning stock from fishery exploitation. The results of the present study suggest that mature female crabs from the Potomac River are the most heavily exploited of the three jurisdictions in the Bay and those from MD are least exploited. While the exploitation fraction of the Potomac River crabs is high, the population size is much smaller than that in neighboring jurisdictions; the annual harvest of mature female crabs in the Potomac is still a fraction of the annual harvest of those in MD and VA: average annual harvest (combined commercial and recreational) of female crabs from 2010-2015 was about 8.3 million lbs in MD, 15.1 million lbs in VA, and 0.7 million lbs in the Potomac River (Eric Johnson, pers.comm.). These figures include harvest of juvenile females

for the soft shell fishery and thus are not direct estimates of mature female harvest but demonstrate the relative scale of the Potomac River fishery.

Sizeable proportions of both the MD and Potomac River crabs were recaptured in VA – 23.4% and 19.4%, respectively. Although female migration is well documented (Hines et al. 1995, Tankersley et al. 1998, Aguilar et al. 2005), these figures give insight into the exploitation of each separately managed crabs that would otherwise be attributed to VA harvest and the fraction of MD and Potomac exploitation that occurs in the jurisdiction of origin, prior to successful migration. Reported harvest of mature females in MD and the Potomac River is not wholly reflective of the total harvest of those originating in these jurisdictions, which merits consideration in management.

Females that originated in upper Bay subestuaries were exploited at a higher rate than those that originated in lower Bay subestuaries. A size disparity was noted in females of the two regions: the average CW of mature females originating in upper Bay subestuaries was 162.4 mm, whereas that of mature females originating in lower Bay subestuaries was 147.8 mm. The larger upper Bay females are likely more fecund than the lower Bay females, based on the significant positive correlation between CW and fecundity (Prager et al. 1990). Based on this result, exploitation of upper Bay female blue crabs, particularly at high rates prior to successful migration, could have a sizeable impact on the reproductive potential of the spawning stock. Dickinson et al. (2006) however, found that while larger crabs produce larger clutches, smaller crabs produce clutches more frequently, making their lifetime production statistically equivalent to that of larger crabs. Relative migration success rates could shed light on the lifetime fecundity of blue crabs in Chesapeake Bay because individuals must migrate to lower Bay spawning grounds to successfully spawn. Unfortunately, the data presented here cannot be used to

estimate this success rate, as release sizes were not proportional to nursery habitat contributions to the spawning stock. Further investigation into the rate at which crabs are exploited in neighboring jurisdictions, migration success, and assessment of potential recruitment overfishing may consider such a design.

Spawning Sanctuary Analyses

Spawning stock exploitation of blue crabs in Chesapeake Bay could be reduced 17% by extending the present Virginia Blue Crab Sanctuary to year-round enforcement. Pooling recaptures from all releases to estimate exploitation after extending the current sanctuary did not prove effective; the majority of recaptures occurred prior to successful migration to lower Bay spawning grounds, limiting ability to assess the sanctuary designed to protect mature females in these areas. The second approach – querying captures in defined lower Bay spawning areas to calculate the proportion of those that occurred in the current sanctuary – likely provides a much more accurate picture of how harvest of the spawning stock may change as a result of year-round enforcement, because it removes captures that occurred prior to successful migration. The sample sizes in the present study were not designed to reflect the populations of the individual tributaries. None of the crabs released in lower Bay subestuaries in the summer were recaptured within the sanctuary, likely due to the timing of the releases (July) and closure of the sanctuary zones (roughly June – September). This study provides the first literature estimate of the potential impact of extending the present sanctuary and should be taken into consideration in relevant management decisions.

Past research has demonstrated the efficacy of the Virginia Blue Crab Sanctuary in protecting the Chesapeake Bay spawning stock (Lipcius et al. 2001, Seitz et al. 2001) and the

results of the present study are in agreement with these assessments, suggesting extended enforcement would further reduce the harvest of mature females in the lower Bay spawning areas. The abundance of mature female blue crabs has increased in Chesapeake Bay since the sub-threshold abundance (68.5 million) estimated in 2014, increasing to 101.5 million in 2015 and again to 194 million in 2016 (CBSAC 2016). The spawning stock grew again this year (2017), jumping to 254 million age 1+ females (Table 5, CBSAC 2017). While the present population is above the target threshold, the average annual spawning stock size is still below the target. Implementation of a year-round sanctuary could increase the average spawning stock size closer to the target threshold.

Summary

Mark recapture studies are an effective means of studying exploitation of female blue crabs in Chesapeake Bay and provide a suite of useful data. The following summarizes the major findings of this study: (1) the overall estimated fishery exploitation rate of mature females in the 2015 blue crab spawning stock in Chesapeake Bay was 10.5%, (2) estimates of fishery exploitation of migrating mature females in individual Chesapeake Bay tributaries varied widely, ranging from 4.0% to 28.5%, (3) of the three management areas, Potomac River crabs were most exploited, MD crabs were least exploited, and sizeable proportions of both were recaptured in VA waters, and (4) extension of the current Virginia Blue Crab Sanctuary to year round enforcement could reduce mature female exploitation in lower Bay spawning areas by up to 17%.

A proper understanding of the population dynamics and fishing pressures on blue crabs in Chesapeake Bay is critical in ensuring the long-term sustainability of the fishery. In recent years, management regulations have used spawning-age females as the bench mark by which to assess

the Bay spawning stock and the population has increased rather sizably; the estimated number of mature females has increased about 271% from 2014 to 2017 (CBSAC 2017). However, increased spawning stock size does not ensure successful recruitment; while mature female blue crabs are at the highest abundance since the formation of the CBSAC, juvenile abundance actually decreased 54% (about 146 million less juveniles) in 2017 despite high mature female abundance (194 million) in 2016 (CBSAC 2017). Spatial understanding of blue crab spawning stock exploitation in Chesapeake Bay provides new information that should be used in concert with other relevant environmental and ecological data to ensure long term successful management of the fishery.

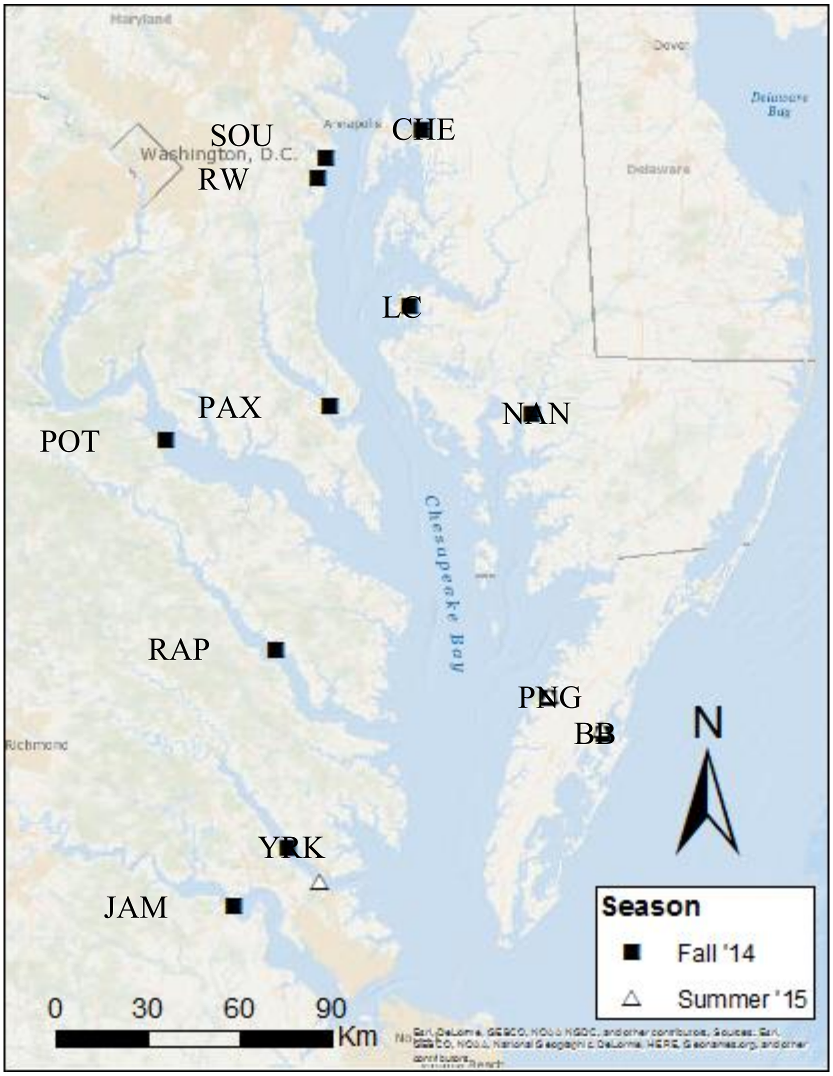

Figure 1 Subestuaries in which female blue crabs were tagged and released. Individuals were released in the Rhode/West River (RW), South River (SOU), Chester River (CHE), Little Choptank River (LC), Patuxent River (PAX), Potomac River (POT), Nanticoke River (NAN), Rappahannock River (RAP), York River (YRK), James River (JAM), Pungoteague Creek (PNG), and Bradford Bay (BB) in fall 2014. These releases are denoted by a black square. Sampling was repeated the following summer (2015) in Bradford Bay, Pungoteague Creek, and the York River. These releases are denoted by white triangles.

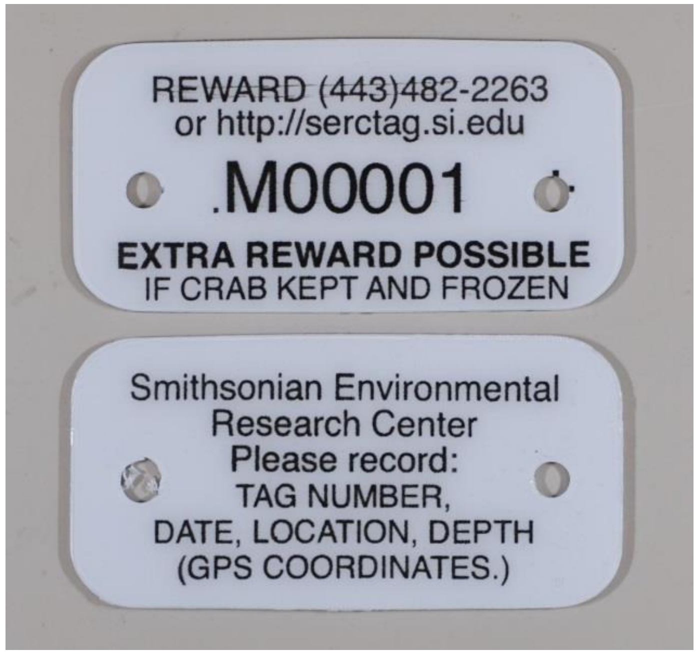

Figure 2 The dorsal surface of each tag (top) is inscribed with a unique identification number, contact information for the Smithsonian Environmental Research Center, the monetary tag value if high value (not pictured), and information regarding a potential additional reward. The reverse side (bottom) indicates that captors should record the tag number, date, location (GPS coordinates) and depth of the recaptured crab.

Figure 3 An adult female blue crab with an over-the-back, white vinyl tag.

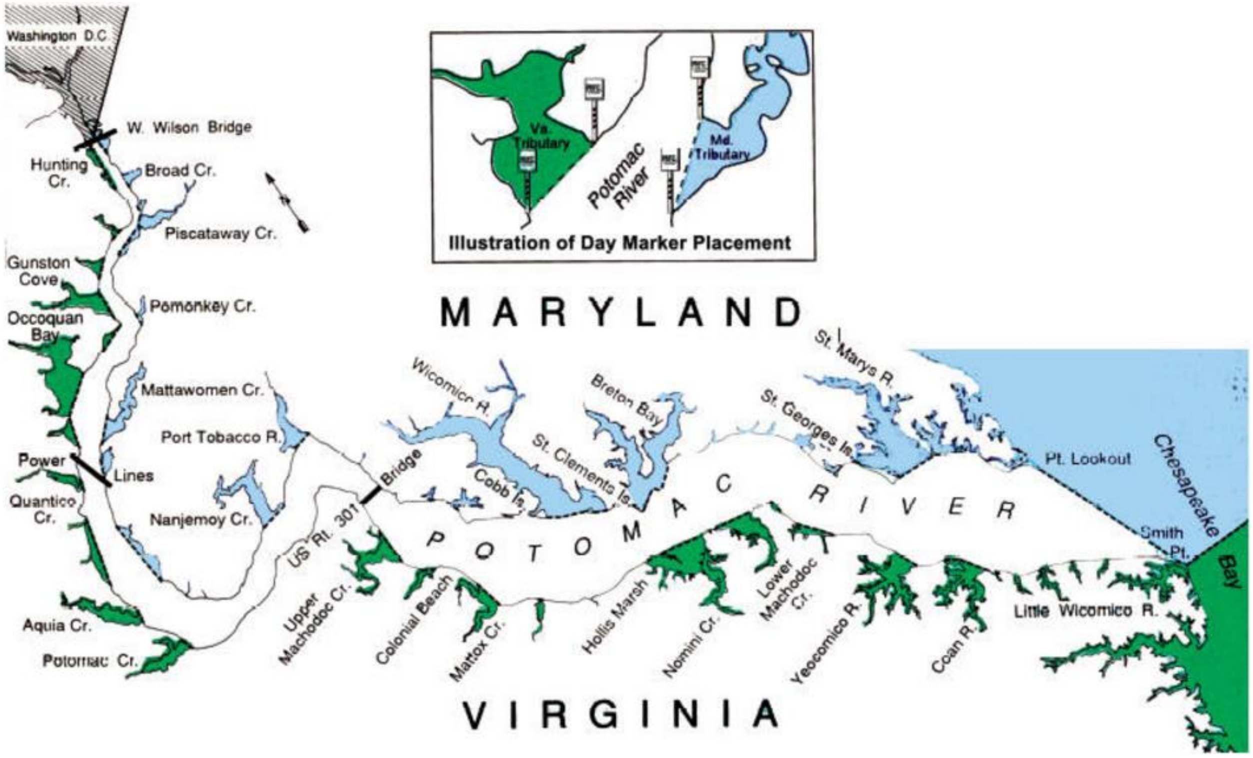

Figure 4 The jurisdictional split of the Potomac River. The tidal mainstem is managed by a Maryland and Virginia bi-state commission, the Potomac River Fisheries Commission. The tributaries on the northern shore are managed by the Maryland Department of Natural Resources and those on the southern shore are managed by the Virginia Marine Resources Commission (Figure: Potomac River Fisheries Commission).

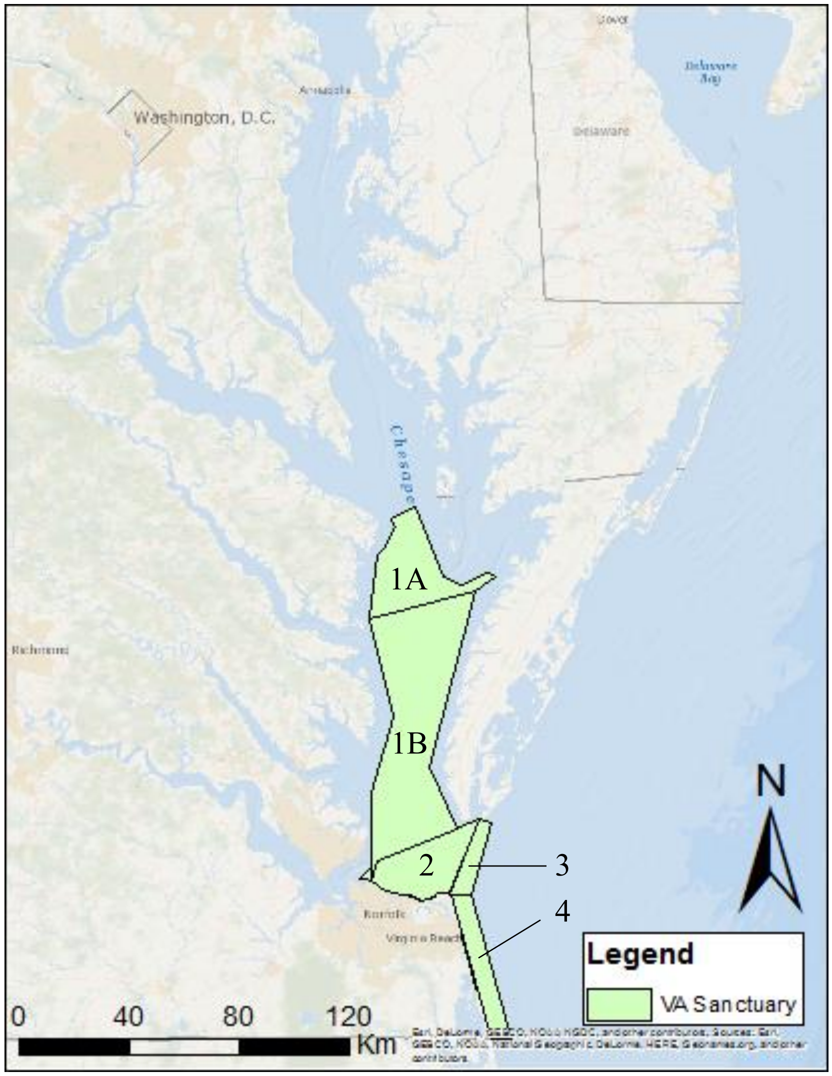

Figure 5 The Virginia Blue Crab Sanctuary in lower Chesapeake Bay as mapped according to the Code of Virginia (4VAC20-752-10 et seq.). The sanctuary is split into five areas: 1A, 1B, 2, 3, and 4. Sanctuary Area 1A is closed to commercial and recreational harvest of blue crabs from June 1 to September 15. Sanctuary Area 1B is closed to commercial and recreational harvest of blue crabs from May 16 to September 15. Sanctuary Areas 2, 3, and 4 are closed to commercial harvest of blue crabs from May 9 to September 15.

Table 1 Subestuaries in which mature female blue crabs were tagged and released. Individuals were released in the Rhode/West River, South River, Chester River, Little Choptank River, Patuxent River, Potomac River, Nanticoke River, Rappahannock River, York River, James River, Pungoteague Creek, and Bradford Bay in fall 2014. Sampling was repeated the following summer (2015) in Bradford Bay, Pungoteague Creek, and the York River. Release coordinates and sample size (n) are given.

2014	Latitude	Longitude	n
Patuxent River	38.347450	-76.478040	486
Rhode/West River	38.868950	-76.514720	489
South River	38.915000	-76.491000	460
Chester River	38.980160	-76.207550	366
Little Choptank River	38.578840	-76.242970	499
Nanticoke River	38.329080	-75.886210	502
Rappahannock River	37.783410	-76.639360	501
Potomac River	38.267900	-76.961150	437
James River	37.183090	-76.761650	482
York River	37.318830	-76.601200	505
Bradford Bay	37.584150	-75.674880	462
Pungoteague Creek	37.670790	-75.834500	500
		Total	5689

2015	Latitude	Longitude	n
Bradford Bay	37.593288	-75.678114	487
Pungoteague Creek	37.673870	-75.833630	398
York River	37.240094	-76.505564	498
		Total	1383
		Overall	7072

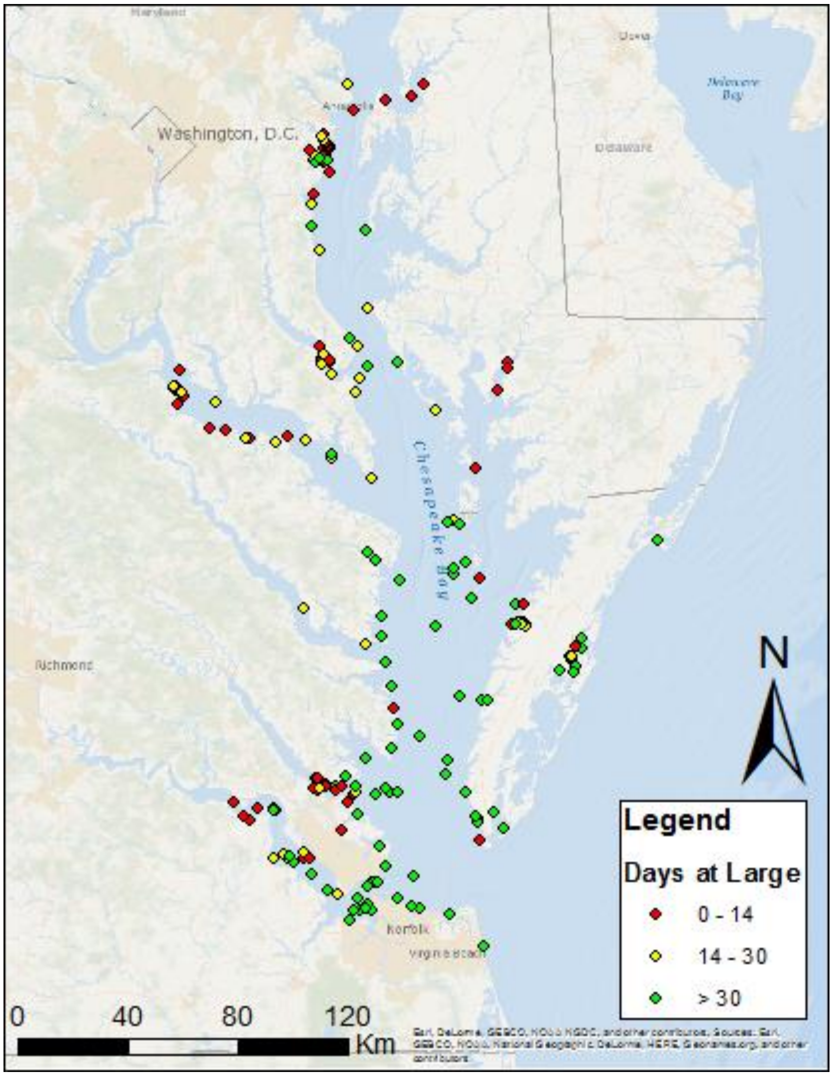

Figure 6 The recapture locations of mature female blue crabs released in 12 subestuaries and one coastal embayment of Chesapeake Bay in fall (September – October) 2014 and summer (July) 2015. Recapture points were symbolized by time at large after release. Red represents recapture up to 14 days after release, yellow represents recapture up to 30 days after release, and green represents recapture greater than 30 days after release. One crab (not pictured) was recaptured in Croatan Sound, NC after 278 days at large.

Table 2 Results of the large scale mark-recapture study conducted on mature female blue crabs in 12 individual subestuaries of Chesapeake Bay in fall of 2014 and summer of 2015. Releases are categorized by year. R_s=# of standard value tags returned, N_s=# of standard value tags released, R_r=# of high value tags returned, N_r=# of high value tags released, λ=reporting rate, and μ=exploitation rate. Tags released in the Little Choptank River were not included in totals. Reporting and exploitation rates could not be calculated for the Little Choptank River and the 2015 Pungoteague Creek because no high value tags were recaptured. Reporting rates marked with an asterisk (*) were assumed to be 1.0 because calculation via *Eq. 1* yielded a reporting rate higher than 100%.

2014	R_s	N_s	R_r	N_r	Total R	Total N	λ	μ
Patuxent River	32	462	1	24	33	486	1.000*	0.068
Rhode River	75	464	2	25	77	489	1.000*	0.157
South River	45	437	3	23	48	460	0.789	0.130
Chester River	33	347	1	19	34	366	1.000*	0.093
Little Choptank River	2	474	0	25	2	499	-	-
Nanticoke River	6	477	0	25	6	502	-	-
Rappahannock River	7	476	1	25	8	501	0.368	0.040
Potomac River	58	415	4	22	62	437	0.769	0.182
James River	52	458	4	24	56	482	0.681	0.167
York River	5	479	0	26	5	505	-	-
Bradford Bay	38	438	4	24	42	462	0.521	0.167
Pungoteague Creek	96	476	6	24	102	500	0.807	0.250
Total	447	4929	26	261	473	5190	0.910	0.100

2015	R_s	N_s	R_r	N_r	Total R	Total N	λ	μ
Bradford Bay	50	487	2	25	52	487	1.000*	0.107
Pungoteague Creek	4	379	0	19	4	398	-	-
York River	28	498	6	22	34	498	0.206	0.285
Total	82	1364	8	66	90	1383	0.496	0.125
Overall	529	6293	34	327	563	6573	0.808	0.105

Table 3 Seasonal exploitation results of the large scale mark-recapture study conducted on mature female blue crabs in 12 individual subestuaries of Chesapeake Bay in the fall of 2014 and summer of 2015. R_s=# of standard value tags returned, N_s=# of standard value tags released, R_r=# of high value tags returned, N_r=# of high value tags released, λ=reporting rate, and μ=exploitation rate. Three different mortality rates were used to adjust exploitation: M=0, M_{ow}=19.25%, and M=0.9. These numbers represent zero natural mortality, overwintering mortality, and natural mortality, respectively. The assumed natural mortality period was 220 days, the average time at large of fall-released crabs that were recaptured in spring and beyond. Fall-released crabs that were captured prior to overwintering were removed from spring exploitation calculations.

Release	Capture	R_s	N_s	R_r	N_r	Total R	Total N	λ	$\mu_{M=0}$	$\mu_{Mow=19.25\%}$	$\mu_{M=0.9}$
Fall	Fall	348	4929	21	261	369	5190	0.877	0.080	-	-
	Spring	94	4581	5	240	99	4821	0.985	0.021	0.0261	0.0305
Summer	Summer	82	1364	8	66	90	1383	0.496	0.125	-	-

Table 4 Results of the large scale mark-recapture study conducted on mature female blue crabs in 12 individual subestuaries of Chesapeake Bay in the fall of 2014 split by region. Releases north of Cove Point (38.3857°N, 76.3812°W) were categorized as upper Bay and those south of there were considered lower Bay sites. Bradford Bay releases were not included as they are not in Chesapeake Bay proper. R_s=# of standard value tags returned, N_s=# of standard value tags released, R_r=# of high value tags returned, N_r=# of high value tags released, λ=reporting rate, and μ=exploitation rate. Reporting rates marked with an asterisk (*) were assumed to be 1.0 because calculation via *Eq. 1* yielded a reporting rate higher than 100%.

Upper Bay	R_s	N_s	R_r	N_r	Total R	Total N	λ	μ
Chester River	33	347	1	19	34	366	1.00*	0.093
South River	45	437	3	23	48	460	0.789	0.130
Rhode River	75	464	2	25	77	489	1.00*	0.157
Total	153	1248	6	67	159	1315	1.00*	0.121

Lower Bay	R_s	N_s	R_r	N_r	Total R	Total N	λ	μ
Nanticoke River	6	477	0	25	6	502	-	-
Patuxent River	32	462	1	24	33	486	1	0.068
Potomac River	58	415	4	22	62	437	0.769	0.182
Pungoteague Creek	96	476	6	24	102	500	0.807	0.250
Rappahannock River	7	476	1	25	8	501	0.368	0.040
York River	5	479	0	26	5	505	-	-
James River	52	458	4	24	56	482	0.681	0.167
Total	256	3243	16	170	272	3413	0.839	0.094

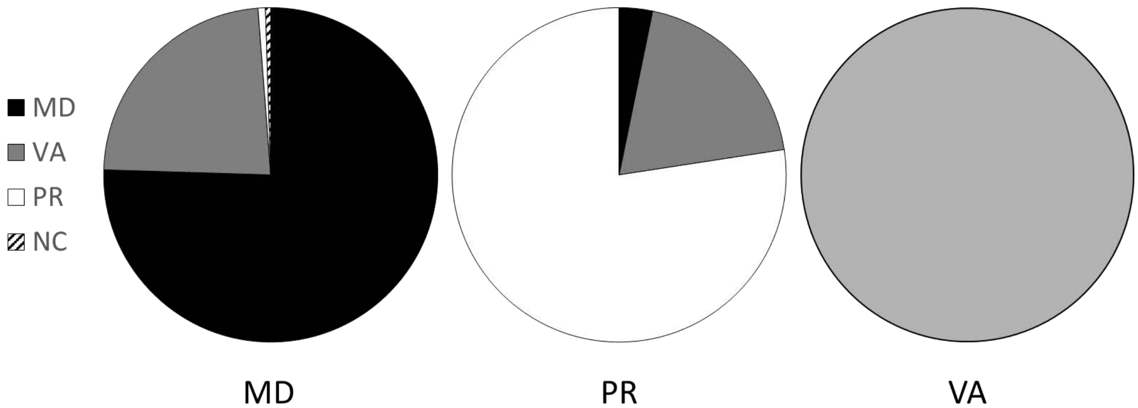

Figure 7 Breakdown of fishery capture of mature female blue crabs in Chesapeake Bay by management area. The blue crab fishery in Chesapeake Bay is managed in three different areas: Maryland (left), the Potomac River (center), and Virginia (right). Each figure represents the exploited crabs from one of these areas. Each slice represents the proportion of recaptured crabs that was caught in the corresponding management area. The Maryland stock was recaptured as follows: 75.6% in MD, 0.5% in PR, 23.4% in VA, and 0.5% in NC. The PR stock was recaptured as follows: 3.2% in MD, 77.4% in PR, 19.4% in VA, and 0.0% in NC. The Virginia stock was recaptured as follows: 0.0% in MD, 0.0% in PR, 100% in VA, and 0.0% in NC.

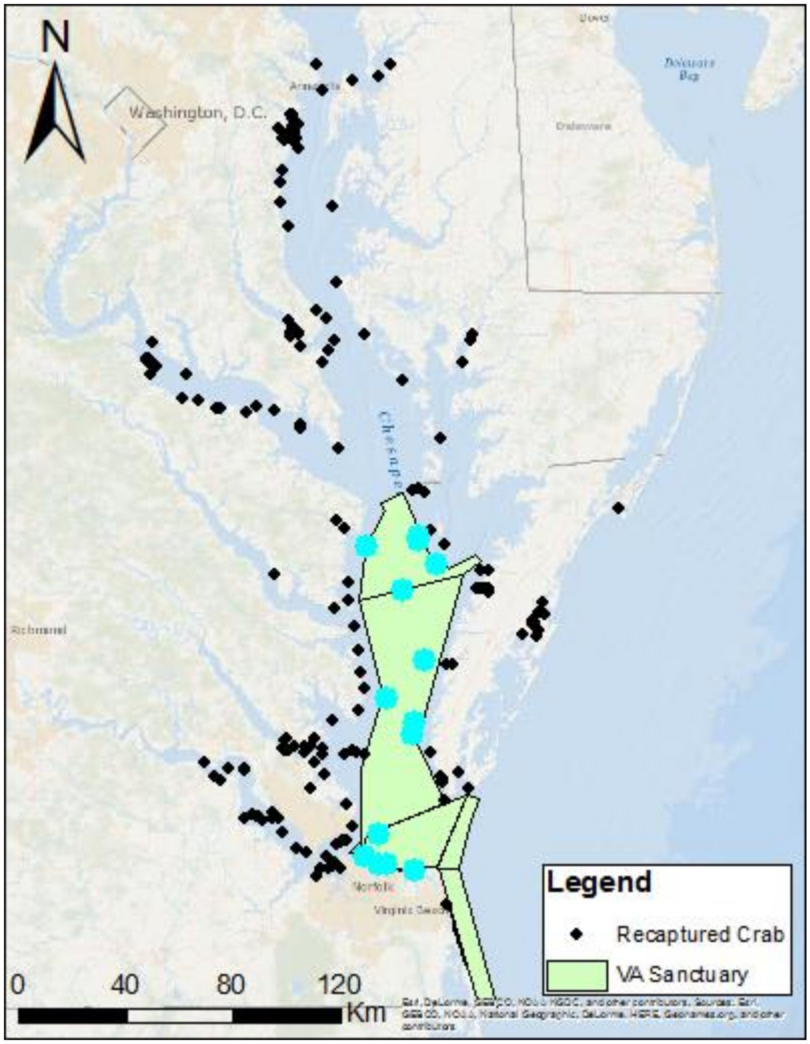

Figure 8 Spatial query of mature female blue crabs recaptured within the Virginia Blue Crab Sanctuary. Crabs captured within the boundaries of the sanctuary are highlighted in light blue. Those recaptured outside the boundaries of the sanctuary are symbolized in black. In total, 22 (21 standard value and 1 high value) tagged individuals were recaptured within the boundary of the sanctuary over the course of the study. One additional recapture (not pictured) came from Croatan Sound, NC, outside the boundary of the sanctuary.

Table 5 The status of juvenile and mature female blue crabs in Chesapeake Bay. Green indicates stocks that are above the minimum threshold and red indicates stocks below the minimum threshold (Table: CBSAC 2017).

Control Rule	**Reference Points**			**Stock Status**						
	Period	**Target**	**Threshold**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Exploitation Fraction (age 0+ female crabs)	Current, Female-specific	25.5%	34% (max)	24%	10%	23%	17%	15%	**16%**	TBD
Abundance (millions of age 1+ female crabs)	Current, Female-Specific	215	70 (min)	190	97	147	68.5	101	194	**254**

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Education

University of North Florida Jacksonville, FL
MS Biology April 2018
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BS Biology August 2014
Major: Coastal Biology

Santa Fe College Gainesville, FL
AA Biology April 2010

Awards

2016 University of North Florida, Biology Graduate Research Enhancement Scholarship
2016 University of North Florida, Coastal Biology Program, Travel Award
2015 Smithsonian Institution Summer Internship Program

Research Experience

Virginia Institute of Marine Science Gloucester Point, VA
Crustacean Disease Ecology Laboratory April 2018 – Present
Laboratory Specialist, Senior

Juvenile Recruitment Trawl Survey December 2017 – March 2018
Field & Laboratory Technician

Juvenile Striped Bass Seine Survey, Juvenile Recruitment Trawl Survey May 2017 – December 2017
Field Specialist

University of North Florida Jacksonville, FL
Blue Crab Dynamics and Ecology January 2015 – April 2018
Graduate Research Assistant

Oyster Reef Assessment June – August 2016
Research Assistant

Assessment & Spatial Analysis of Invasive Lionfish, Coral Stress Response August 2013 – August 2014
Undergraduate Research Assistant

Smithsonian Environmental Research Center Edgewater, MD
Blue Crab Population Dynamics August – November 2014
Graduate Research Fellow/Paid Intern June – August 2015

Florida Department of Environmental Protection Jacksonville, FL
Horseshoe Crab Survey April 2013 – May 2015
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Teaching Experience

University of North Florida Jacksonville, FL
Graduate Teaching Assistant, Gen. Biology I Lab Fall 2016

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Graduate Assistant, Marine Field Studies in Florida April – June 2016

Conference Presentations

Corrick C.T., Johnson E.G., Ogburn M.B., Aguilar R., and A.G. Hines. Spatial variation in fishing mortality of mature female blue crabs (*Callinectes sapidus*) in individual subestuaries of the Chesapeake Bay. Oral presentation delivered at the 46th Annual Benthic Ecology Meeting, Myrtle Beach, SC, April, 2017.

Corrick C.T., Johnson E.G., Ogburn M.B., Aguilar R., and A.G. Hines. Spatial variation in fishing mortality of mature female blue crabs (*Callinectes sapidus*) in individual subestuaries of the Chesapeake Bay. Poster presentation delivered at the University of North Florida Natural Sciences Poster Session, Jacksonville, FL, November, 2016.

Corrick C.T., Johnson E.G., Ogburn, M.B., Aguilar R., and A.G. Hines. Spatial variation in fishing mortality of mature female blue crabs (*Callinectes sapidus*) in individual subestuaries of the Chesapeake Bay. Oral presentation delivered at the Annual Meeting of the Tidewater Chapter of the American Fisheries Society, Edgewater, MD, April, 2016.

Corrick C.T., Johnson E.G., and M.B. Ogburn. Direct and indirect effects of fishing on blue crab (*C. sapidus*) recruitment. University of North Florida. Poster presentation delivered at the University of North Florida Natural Sciences Poster Session, Jacksonville, FL, October, 2015.

Johnson E.G., Swenarton M.K., **Corrick C.T.**, Green M. Population biology of invasive lionfish in northeast Florida. Poster presentation delivered at STARS: Scholars Transforming Academic Research Symposium, University of North Florida, Jacksonville, FL, April, 2014.

Corrick C.T., Johnson E.G., and M.K. Swenarton. Derbies as an effective means for sample collection and analysis of invasive lionfish in Northeast Florida. Poster presentation delivered at the 43rd Annual Benthic Ecology Meeting, Jacksonville, FL, March, 2014.

Research Contributions

Swenarton, M.K. 2016. Population Ecology of Invasive Lionfish (*Pterois volitans/miles*) in the South Atlantic Bight. UNF Theses and Dissertations. 626. Acknowledged for contribution.

Johnson E.G. and M.K. Swenarton. Age, growth and population structure of invasive lionfish (*Pterois volitans/miles*) in northeast Florida using a length-based, age-structured population model. PeerJ 4:e2730. Acknowledged for contribution.

Public Outreach

2017 Volunteer at the Peninsula Salt Water Sport Fisherman's Association's Cobia Bowl fishing tournament
2016 Appearance in documentary film, "Beautiful Swimmers Revisited" (uncredited)
2014 Collaborator and volunteer at REEF Key Largo Lionfish Derby, appearance on "Bizarre Foods America" television program (uncredited)
2014 Collaborator and volunteer at Northeast Florida Lionfish Blast spearfishing tournament
2014 Collaborator and volunteer at El Cheapo Sheepshead Tournament