ASSESSING THE EFFECT OF CLIMATE VARIABILITY ON THE SOUTH CAROLINA RECREATIONAL AND COMMERCIAL BLUE CRAB FISHERY

A thesis submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

in

ENVIRONMENTAL STUDIES

by

KELSEY LYNN MCCLELLAN

May 2017

at

THE GRADUATE SCHOOL OF THE UNIVERSITY OF CHARLESTON, SOUTH CAROLINA AT THE COLLEGE OF CHARLESTON

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ABSTRACT

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Blue crabs are an important commercial fishery in South Carolina, but landings have decreased over the past 15 years, sparking debate about how to effectively manage this population. It is unclear whether this decline is more related to drought or changes in fishing effort. The objective of this study is to measure recreational catch-per-unit-effort (CPUE) and total recreational catch of blue crab in South Carolina coastal waters, and determine the impact of recreational fishing pressure on the commercial fishery, and how this interaction changes with flow conditions and hypothetical seasonal closures for female harvest. Using a spatially-explicit individual-based population model, the South Carolina Blue Crab Regional Abundance Biotic Simulation (SCBCRABS), we compared the efficiency of commercial versus recreational traps during periods of flood, normal and drought conditions, and during hypothetical seasonal closures (no harvest of females, no harvest of females during full spawning season, partial harvest of females during spawning season). We found a significant decrease from 1997 in the recreational fishery (-63%), with evident seasonal catch patterns, and shifts in preferred gear type used from 1997 to 2015. Additionally, SCBCRABS modeled the phenomenon of trap interference with competition between commercial pots.

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1. INTRODUCTION

Callinectes sapidus is an economically and ecologically important marine species in South Carolina (Blue Crab Update 2007, Childress 2010, Parmenter 2012). In South Carolina, blue crab accounts for 10% of the total value of all commercial landings (Blue Crab Update 2006). Since 1988, blue crab pots (traps) have been used by the Crustacean Research and Monitoring Section of the South Carolina Department of Natural Resources (SC DNR) to evaluate relative abundance in several estuaries in South Carolina. During 2013, SC DNR fisheries-independent surveys continued to collect relatively low numbers of blue crabs similar trends observed in 2007-2010 (Fowler and DeLancey 2014). Blue crab abundance as indicated by fisheries-independent sampling and fisheries landings over the period 1998-2012, has been coincident with a period of reduced rainfall and river runoff (Fowler and DeLancey 2014).

Although 2013 experienced significantly more rainfall than previous years, the blue crab population has not recovered to historical levels possibly due to the record high rainfall of the summer of 2013 or perhaps an insufficient time for spawning stocks to recover in the face of continued heavy fishing pressure (Fowler and DeLancey 2014). This sentiment was again discussed by several commercial crab fishermen at the SCDNR'S Marine Advisory Committee meeting in Charleston in August 2015.

One of the key knowledge gaps for blue crabs identified from the "Research

Needs for the Sustainable Management of Crustacean Resources in the South Atlantic Bight" workshop held at Marine Resources Research Institute (MRRI) April 9-10, 2014 was the lack of a state-of-the-knowledge report concerning the impacts of climate and habitat change on blue crab populations. Climate change can encompass a multitude of environmental factors, but one of the most influential to all estuarine-dwelling marine species is salinity which influences blue crab habitat utilization for different life stages (Van Den Avyle et al. 1984; Mense and Wenner 1989). Stark changes in salinity gradients in coastal South Carolina were observed during the long-term period of reduced rainfall that began in 2000, and if that drought is related to changing climatic patterns, it could be correlated with decreasing catches of blue crabs in commercial pots (Parmenter 2012). With a lack of rainfall, the more valuable, larger males move above the legal fishing line in search of fresher water, while the ovigerous (sponge) female crabs move seaward to higher salinities waters to spawn (Van Den Avyle et al. 1984; Archambault et al. 1990). Many crab fishermen believe that the decrease in the catch is directly related to the movement of males up river to follow that salt water wedge. While the SC DNR fisheries independent catch data corroborates what the fishermen are observing, i.e. a decrease in crab abundance, we do not know whether this decrease is due to the complete absence of large blue crabs or just a shift in the habitat of these preferred individuals.

Another knowledge gap for blue crab exists within the recreational fishery sector. While SC DNR has commercial landings and a rough catch-per-unit- effort of blue crabs due to trip tickets that commercial dealers must report, the landings of recreational blue crab fishermen are relatively unknown. The last state-wide estimate of the total catch of recreational blue crab fishermen was completed in 1997 by the SC DNR Office of

Fisheries Management. This was prior to the intermittent periods of drought, between 1999 - 2002 and it is estimated that the recreational catch was between 21 and 28% of the total catch (both commercial and recreational) in South Carolina (Low 1998). Although complaints from recreational fishermen indicate poor catch rates, there are no data to determine if the same decline in crab abundance exists in recreational fishery. Therefore, this project proposes to update the state-wide recreational blue crab catch information for comparison with the 1997 estimates. This estimate will be derived through a postcard survey and will be compared with a concurrent field study of recreational catch data along a salinity gradient. As crabs can move to follow salinity changes, a potting survey at stationary sites along a river system conducted over the summer months will allow us to track changes in catch per unit effort. These data can then be examined to determine if recreational catch per unit effort is impacted by changes in salinity, and, if so, in what direction those changes occur.

The study will combine 1) fisheries independent surveys, 2) fishery dependent surveys, and 3) an individual based model (IBM) to estimate how the commercial and recreational blue crab fishing pressure differs along a salinity gradient and the overall economic impacts of these changing environmental factors on the fishery.

(1) Fisheries independent survey of recreational fishery along a salinity gradient during the peak recreational fishery in Ashley River, South Carolina (May-October). Using GIS analysis and license data, we will determine where the highest density of recreational crabbers occurs in the Charleston area. The study site will encompass a range of salinities, including above the legal saltwater/freshwater dividing line, experienced during both drought and flood conditions. All environmental data

(water temperature, salinity) and biological data (abundances of sublegal and legal crab, separated by sex) will be used to inform the IBM (see #3). The fisheries independent portion of this study is limited to the Ashley River.

(2) Fisheries dependent surveys of the recreational fishery will incorporate both conventional methods of a postcard mail-out (based on the addresses of license holders) and online surveys. This will also occur during the peak recreational fishery in South Carolina (one mailing during July/August and another in September/October). The crabbers will be asked about gear used, catch, legal crabs kept, pot location, soak time. Furthermore, the immediate data input by recreational crabbers may eliminate a recall bias in reporting catch data. This study was organized to compare catch rates from 2017 to findings reported by Low (1998) in an SC DNR report.

(3) Combination of fisheries independent and dependent data into an already established individual based model for blue crabs in South Carolina's estuaries. Using the SCBCRABS model, adjusted to the salinity profile of the fisheries independent data collected from #1, the model can then be adjusted to distinguish between recreational crab pots and commercial pots based on the differences of legal soak times and distance from river bank. We would then alter three conditions within the model to determine the impacts on the legal-sized blue crab abundance: recreational removal of crabs, commercial removal of crabs, and combined recreational and commercial efforts. This will enable us to directly compare

recreational and commercial fisheries to determine how the blue crab population responds to the fishing pressures. The commercial landings data will be collected from the SCDNR commercial landings dataset. In addition, the revised IBM model will incorporate seasonal variation in commercial crab pot density and position.

2. SOUTH CAROLINA BLUE CRAB RECREATIONAL FISHERY: THEN AND NOW, A COMPARISON OF THE SOUTH CAROLINA FISHERY IN 1997 AND 2015

Introduction

Recreational fishing pressure can be extensive and has the potential to not only decrease the abundance of the target species, but can also lead to the collapse of an ecosystem (Altieri et al. 2012). Top-down trophic cascades are caused by the removal of top-level predators from an ecosystem, and recreational fisheries often target the top-level predators (Coleman et al. 2004, Altieri et al. 2012). Recreational fishing is a world-wide activity, with global recreational landings exceeding 10 million tons (Altieri et al. 2012, Cooke and Cowx 2004). Historically, recreational fishing was not considered to compete with commercial fisheries in terms of harvest and stock depletion, and thus the impacts of recreational fishing were relatively overlooked in comparison to the commercial fishing sector (Kearney 1999, McPhee et al. 2002, Cooke and Cowx 2004, 2006, Altieri et al. 2012). However, overlooking the recreational fishery may have been in error, as recreational harvests have been found to compete with commercial harvests in coastal regions (Altieri et al. 2012); in addition, the recreational fishing sector increased by over 20% in US coastal states from 1983-2003 (Sutinen and Johnston 2003, Coleman et al. 2004).

Blue crabs (*Callinectes sapidus*) support substantial commercial and recreational fisheries along their range—notably in the Gulf of Mexico, South Atlantic Bight, Chesapeake Bay, and Delaware Bay (Milliken and Williams 1984, Miller et al. 2000, Muffley et al. 2007). Traditionally, blue crabs are commercially fished using baited pots, while recreational fishers use a variety of methods based on personal choice, cost, and ease of transport (i.e., baited pots, chicken necks, drop nets). While the commercial landings of hard blue crabs are documented routinely, the same cannot be said for the recreational side of the fishery. To evaluate and monitor changes in recreational fishing effort in these systems, a fisheries dependent survey, or a survey dependent on the responses from fishery participants (both commercial and recreational), is necessary. Nationally, the Marine Recreation Fisheries Statistical Survey conducts intercept surveys to establish marine finfish recreational fisheries databases. Crustacean recreational fisheries, on the other hand, are not recorded and reported as thoroughly. Blue crabs, for instance, are managed at the state level, whereas many marine finfish fisheries are under regional federal regulations. Historically, the methods used to obtain fishery dependent blue crab recreational data also vary, and the most prominent methods used are intercept surveys, telephone surveys, and mailed survey postcards (Low 1998, Muffley et al. 2007, Ashford et al. 2011).

Commercial landings of hard blue crab can fluctuate substantially from year to year, but there has been a decline in hard blue crab landings along the US Atlantic Coast in recent years (Lee and Frischer 2004, Blue Crab Update 2007). However, trends in the recreational blue crab fishery are currently unknown in these states, as the recreational component of any fishery is not routinely surveyed and difficult to quantify (Sharov et al.

2003). Previous estimations of the blue crab recreational fishery along the US Atlantic coast have varied, but clearly indicate that it is an important contributor to the overall fishery. In 2009, recreational harvest was assumed to account for approximately 8% of the total Chesapeake Bay-wide commercial harvest of males according to the Chesapeake Bay Stock Assessment Committee (CBSAC) (2016). Females were excluded from the figure as recreational harvest of females in no longer allowed in Maryland (CBSAC 2016). In the Chesapeake area, a 52% increase in estimated recreational harvest was observed from 2014 to 2015, from 2.3 million pounds to 3.5 million pounds (CBSAC 2016). Combining the commercial harvest and estimated recreational harvest, 53.1 million pounds of blue crabs were harvested from the Chesapeake Bay and its tributaries in the 2015 crabbing season (CBSAC 2016). In New Jersey, one recreational blue crab survey in 2007 estimated the Delaware Bay recreational catch to be 4.17 million crabs, with 1.92 million crabs retained by harvesters. This accounts for approximately 20% of the New Jersey commercial harvest in the Delaware Bay (Muffley et al. 2007). Muffley et al. (2007), makes the distinction between anglers who catch crab and those who harvest crab, not all crabs caught are of legal limit, and thus, are not harvested. Another study, conducted in the Chesapeake region, reported an average of 17% of their 1,147 interviewees' as holding recreational crabbing licenses, with an average catch of 12.1 crabs per trip (Miller et al. 2000). In Florida, Steele and Bert (1998) found that 18% of all tag returns made during a 1983 to 1985 blue crab tagging study were from recreational crabbers. The recreational blue crab fishery in South Carolina is also substantial with the last-reported estimate between 21 and 28% of the total harvest (both commercial and recreational) in 1997 (Low 1998).

To compare recreational blue crab landings among coastal Atlantic states, it is useful to know that recreational licensing and regulations vary from state to state; some states restrict catch, while others require recreational licenses and permits to fish or use certain gear types. For example, due to management restrictions after 2009, the recreational harvest of female blue crabs is not allowed in the state of Maryland or in the Maryland tributaries of the Potomac River (Chesapeake Bay Blue Crab Advisory Report 2015). Regulations in other Atlantic states, such as New Jersey, involve a complete closure of both the commercial and recreational fisheries in the Newark Bay Complex, a heavily populated area (Pflugh et al. 2011). In areas where crabbing is allowed, such as Delaware Bay, there are gear, size, and seasonal restrictions. South Carolina manages the recreational marine fisheries by requiring anyone 16 years or older to possess a Saltwater Recreational Fishing License to harvest fish, shrimp, and blue crab; does not allow the harvest of sponge crabs; and has a minimum size limit of five inches (width) (SCDNR 2016).

In South Carolina, hard blue crab commercial landings account for ~25% of the average total value of all commercial fisheries landings; the blue crab commercial harvest was valued at $4.7 million in 2015, second only to penaeid shrimp (SCDNR, Office of Fisheries Management). In the past, the blue crab fishery was considered the most stable fishery in the state of South Carolina, with average annual landings of 6 million pounds (Blue Crab Update 2007). Over the last 15 years, the South Carolina blue crab population has declined substantially as indicated by both fisheries dependent and independent data (SCDNR, OFM, Crustacean Monitoring and Research Section). While the commercial fishery for blue crab is monitored through landings data, there is no annual monitoring of the recreational fishery since 1997. Although anecdotal reports from recreational crabbers also suggest that crab abundance has declined, it is unknown if the recreational fishery has observed the same degree of decline as observed in the commercial fishery.

The blue crab recreational fishery in South Carolina is economically valuable, as it incorporates licensing fees, local landing access fees, and gear purchased from local bait shops. While recreational fishing may still account for a quarter of all blue crabs fished, there are factors which may influence the rate of recreational fishing. On an individual level, health, time, cost, limited resources, social structure, and environmental health are reasons why an angler may join in or drop out of a recreational fishery (Fedler and Ditton 2001). Additionally, a growing population likely results in more entry into the fishery. With recent increases in the human population along the South Carolina coast (+15.3% between 2000 and 2010; U.S. Census Bureau 2015), it is possible there has been a likewise increase in fishing pressure for blue crab. In a 2003 study, it was predicted that the total population of the Charleston region alone (Berkeley, Charleston, and Dorchester counties) will increase by ~50% from 1994 to 2030 (Allen and Lu 2003). The counties of Charleston and Jasper underwent 10-19.9% population increases, Berkeley county 20.0-29.9% increase, while Horry, Dorchester, and Beaufort counties experienced a 30-41.6% population increase from 2000 to 2010 (U.S. Census Bureau 2015).

My study was developed to gain insight to the fishing behaviors for blue crab by recreational license holders, including frequency of fishing, and fishing methods. Basic study methods mimic those used by Low (1998) to facilitate direct comparisons. A goal was to determine catch-per-unit-effort estimates and total recreational catch of blue crab. I further hypothesized that the rapid population growth of the coastal counties of South

Carolina increased entry into the recreational blue crab fishery. Concurrent with increasing fishing pressure, I investigated current proportion of recreational catch to commercial catch as compared to Low's 1997 observations (Low 1998).

Methods

Survey Design

A postcard survey of the recreational blue crab fishery was utilized to survey fishing effort and catch. As previously done in 1997, this survey was conducted during the perceived peak of the recreational fishery in South Carolina (July - October), and all methods detailed below mimicked the previous mail-out survey (Low 1998). To assess the current recreational fishery statewide, 20,001 postcards (Appendix A) were mailed out to a subset of the recreational marine fisheries license holders who were on file as of July 2015, in South Carolina (N=261,093). The 2015 survey was limited to residents of South Carolina. This study was based upon a 1996 study conducted by the South Carolina Department of Natural Resources (SCDNR) which concluded that percentage of nonresidents who crabbed recreationally was significantly lower than that of in-state residents (Waltz 1996). Two mail-outs were made to eliminate recall bias by the respondent: one in September 2015 (N=10,000) to obtain July/August fishery information, and one in November 2015 (N=10,001) to obtain September/October fishery information. The 2015 sample population (N=20,001) was randomly selected at one time to ensure no duplication of respondents between the two mail-out cohorts. The sample population was stratified by coastal (75%) and non-coastal (25%) counties, and the number of mail-outs assigned to each county was similar in proportion with the number of saltwater recreational fishing licenses in that county (Table 2-1).

The postcards were used to capture county fishing pressure, average number trips made, type of crabbing location (i.e., boat, dock/bridge, bank/beach, pay-to-fish fishing pier, and other), type of gear used, and average number of crabs caught per trip (Appendix A). Respondents could choose to either mail the pre-paid postcard or complete an identical online survey. The data were separated into coastal and non-coastal counties for interpretation, and each group of counties was assigned a number ranging from (1-7, representing regions of the state) as per methods in Low (1998) (Table 2-1).

Survey Return and Response Rate

Return rate and response rate for each season, region, and year were compared to determine if there were differences in fishery participation. Respondents that listed their county as "other" were removed from analyses. All returned-to-sender mailouts were also removed from the number of total postcards mailed. A 3-way contingency table tested for differences in survey response rate by region and were compared with equivalent data from Low (1998) to test for influencing factors in response rate (Lowry 2016). A two-factor ANOVA without replication was used to analyze seasonal differences between the years (1997, 2015); these analyses were conducted using R v3.3.1 (R Development Core Team, 2016). The count data for returned postcards from both summer and fall were summed on a county level and incorporated into a response density map using ArcGIS 10.4.1. The data were joined with the county data collected from Environmental Systems Research Institute (ESRI) for visual interpretation.

Crabbing location and method of fishing

Both the crabbing location (i.e., boat, dock/bridge, bank/beach, pay-to-fish fishing pier) and fishing method (i.e., handline, pot, dropnet) are descriptive variables which inform this study of fishing habits within the recreational fishery and may demonstrate how fishing behaviors have changed between 1997 and 2015. The response data were categorized by season (summer or fall) and categorized by region number (1-7). The effect of season, region, and year on crabbing location and fishing method was examined using two separate mixed-effects generalized linear models (GLM) with a Poisson distribution (R package: stats). The response variable in these models was frequency of preferred crabbing location or fishing method reported, while season, region, and year were treated as fixed effects in each model. The interaction terms (year x region x season) were added stepwise into the model as mixed effects. A Hosmer and Lemeshow goodness of fit (GOF) test was conducted to analyze the fit of the mixed-effects GLM. These analyses were conducted using R v3.3.1 (R Development Core Team, 2016).

Estimated Catch

Estimated catch was calculated for each region during both the summer and fall seasons through a stepwise formula. Responses were eliminated if respondents did not report the number of trips made or if they did not report their county. First, the number of "Estimated Crabbers" was calculated from the percentage of respondents that reported crabbing and scaled up by the number of total license holders for that region. The total estimated number of crabs caught was calculated by multiplying the estimated crabbers by the total number of crabs that respondents reported catching. The 2015 estimated total trips were calculated by multiplying the estimated crabbers by the total number of trips respondents reported taking. The "2015 average" was the average trips per crabber. The "observed crabs per trip" was the number of crabs caught divided by the number of trips taken for each individual respondent. The observed result of crabs per trip was used to calculate the observed Catch Per Unit Effort (CPUE):

$$\left(\frac{\frac{Observed\ crabs}{Trip}}{Observed\ \#\ Respondents}\right) * Estimated\ \#\ of\ Trips$$

(1

Observed CPUE was multiplied by the estimated number of crabbers to calculate the Estimated CPUE for each region and season for 2015. Due to unavailability of data, the estimated CPUE could not be calculated for 1997. The other metric of reporting total landed crabs was estimated total catch, which was calculated per zones (1-7) for summer and fall, 1997 and 2015:

$$\frac{\sum Crabs\ Caught}{\sum Trips}$$

(2

The total catch of blue crabs per total trips per reporting region was used for expansion estimates (Low 1998) to compare catch rates between 1997 and 2015. It is pertinent to understand that only total estimated catch was used to compare catch rates between seasons and between 1997 and 2015, as Low (1998) did not calculate CPUE. Total estimated catch was converted into pounds to compare recreational and commercial fishing pressures. To convert catch to pounds, it is assumed there are 100 crabs per bushel (Low 1998), then apply a multiplier of 40 pounds/bushel (Low 1998). Commercial blue crab landings data for 1997 and 2015 in South Carolina were provided by the Office of Fisheries Management (OFM) of the SCDNR. Combined commercial and recreational catch was used to compute the percentage attributable to the recreational harvesting sector. In previous studies, there was a differentiation of crabs caught and crabs harvested—if a crab was caught, it was not necessarily kept by the commercial watermen or recreational anglers. If a crab was harvested, then it was culled for the respective fishery. For this study, catch and harvest are interchangeable terms.

A two-way ANOVA was performed to determine the effect of year and season on recreational catch estimates. Once the recreational catch was converted into pounds, two-way ANOVAs were run to compare the total commercial and recreational landings for 1997 and 2015. The price per crab was averaged from July and August for "Summer" and from September and October for "Fall". Total values were calculated using estimated price per crab using the following prices/crab: Summer 2015 $1.40/crab and Summer 1997 $0.52/crab and Fall 2015 $1.00/crab and $0.42/crab Fall 1997 (OFM, SCDNR). Since recreational crabbers do not sell their catch, the "Price per pound" is only used to calculate the value of these crabs if they had been caught and sold commercially. Generally, when considering recreational fisheries, the value of the fishery is based upon the amount of money spent in prosecuting the fishery (gas, bait, gear, travel, hotel, etc.) (David Whitaker, pers. comm.).

Results

Survey Return and Response Rate

Of the sample population, 1,562 postcards were received from the September mail-out and 1,488 from the November mail-out for an overall response rate of 15.3%, n = 3,117. In comparison, the Low (1998) survey had a higher overall return rate of 28.3%, n = 3,383 (Figure 2-2). In 2015, the ratio of completed and returned surveys was higher from the noncoastal counties, which contrasted with the 1997 survey in which the coastal counties had a higher ratio of completed and returned surveys. Comparing between the two surveys (1997 and 2015), the interaction between year and season significantly impacted the regional response rates (Table 2-2). While the ratio of responding postcards was highest in the noncoastal counties, the noncoastal regions (1-4) had the overall lowest total number of responding postcards. The noncoastal counties with the higher return rates were counties with large cities, such as Greenville County (Figure 2-1). There was no significant seasonal effect on return rates between 1995 and 2015 (2-Way ANOVA; F (1,3) =161.45, $p > 0.5$) (Table 2-2; Table 2-4).

Crabbing Response Rate

Overall, 14.4% reported crabbing activity in 2015, with 7.4% from noncoastal counties and 17.6% from coastal counties. In comparison, Low (1998) reported 19.8% of noncoastal respondents reported crabbing activity and 32% of coastal respondents reported crabbing in 1997 (Figure 2-3; Table 2-4). Both the 2015 and 1997 surveys documented the majority of those that reported crabbing activity came from coastal counties for both sampling periods (Figure 2-3; Table 2-4; Low 1998). While there was no seasonal effect overall on response rate, there were regional and seasonal effects on crabbing rates (Table 2-3). Those who live in noncoastal regions were less likely to crab (mixed-effects GLM; Z=6.577, $p < 0.0001$; Table 2-3) and all respondents were more likely to crab in the summer (mixed-effects GLM; Z=-5.162, $p < 0.0001$; Table 2-3).

Crabbing Location

Of those respondents that reported crabbing activity in 2015, docks and bridges were the preferred crabbing locations for both coastal and noncoastal crabbers for both seasons (46-61% preferred or used those locations). This is representative of a shift from the 1997 survey, where boats were reported as the preferred crabbing location in the fall for both coastal (45%) and noncoastal respondents (60%); boats were also as preferred as docks/bridges in the summer (mixed-effects GLM; Z=8.203, $p < 0.0001$; Figure 2-4;

Table 3-5; Low 1998). There was a significant shift of preferred crabbing locations for noncoastal respondents from 1997 to 2015 (mixed-effects GLM; Z= -2.329, $p = 0.02$; Figure 2-4; Table 3-5). Banks and beaches were not highly utilized crabbing locations in either 1997 or 2015 (Figure 2-4). For both 1997 and 2015, the noncoastal respondents used banks/beaches more than their coastal counterparts in both summer (13-21%) and fall (12-25%). In the 2015 survey, an additional category ("pay-to-fish-pier") was added, but the category was not popular with the 2015 respondents with less than 1% using the "pay-to-fish-pier". The category was dropped for statistical analyses, as 1997 did not have a comparable field.

Method of Fishing

There was a significant interaction between the influence of year on gear choice for both pot gear choice preference (mixed-effects GLM; Z= -5.369, $p < 0.0001$; Table 2-6) and for handline gear (mixed-effects GLM; Z=5.97; $p < 0.0001$; Table 2-6). Of those that reported crabbing activity in 2015, crab pots were the preferred method of recreational fishing for both coastal and noncoastal anglers for both seasons (41-48% preference) (Figure 2-5). These data were in agreement with previous data from Low (1998), who also reported a preference to use crab pots, but there was an increase in the frequency of using drop nets and a decrease in using baited strings in 2015 (Figure 2-5).

Estimated Catch

The total number of blue crabs recreationally fished was calculated two ways: the estimated total catch-per-unit-effort (CPUE) and estimated total recreational catch. The way these values differ is that CPUE calculations are the sum of crabs/trip/ person (Equation 2) while estimated total catch (ETC) accounts for the estimated number of trips taken multiplied by the average number of crabs caught per trip (Equation 2). The CPUE for summer 2015 was 304,434, while the summer 2015 estimated total catch was 251,477 crabs (Table 2-7). In fall 2015, total catch as with overall CPUE was 502,424, and the estimated total catch using (Equation 2) was calculated at 319,584 crabs (Table 2-7). Both the CPUE and estimated catch rate were higher in fall than summer (Table 2-7), but still the estimated total catch rate was lower in 2015 than in 1997, despite a larger effort. In summer 2015, there was a total of 30,903 estimated crabbers participating in the fishery—this is almost double the number of estimated crabbers in 1997 (n=16,449). The fall 2015 experienced a slight increase in the number of estimated crabbers, with 36,538 estimated crabbers in the fishery, contrary to fall 1997, when there was a decrease in the number of estimated crabbers (15,117).

Overall, in 2015 there were 63% fewer crabs recreationally caught than in 1997 (Table 2-8). In summer 2015, there was an overall 65% reduction in catch (Table 2-8) with the largest percent reduction being in coastal Zone 5 (a 71% reduction from 1997 to 2015) In fall 2015, there was an overall reduction in recreational catch of 62% compared to fall 1997, with the largest percent reduction in coastal Zone 6 of 71% (Table 2-8). The 1997 total estimated recreational catch for both seasons and all regions was 832,958lbs; the 2015 total estimated recreational catch for both seasons and all regions was 133,273lbs., an 84%reduction.

There was a significant difference in estimated total catch between years (2-way ANOVA; $F(1, 3) = 698.45$, $p = 0.02$), but no significant difference between seasons (2-way ANOVA; $F(1,3) = 1.91$, $p = 0.39$). In 1997, there is a significant difference between estimated recreational landings and commercial landings (2-way ANOVA; $F(1,3) = 102.88$, $p = 0.06$), but no significant difference in the relative size of the summer and fall catch for both the recreational fishery and commercial crabbing fishery (2-way ANOVA; F (1,3) = 1.60, p = 0.4). In 2015, the recreational sector landed significantly fewer crabs than the commercial fishery, but this was not influenced by season within recreational and commercial crab landings (2-way ANOVA; F (1,3) = 1.34, $p=0.45$). In 2015 and 1997, the estimated total recreational catch value decreased considerably between summer and fall (Figure 2-6), and the estimated total catch value of landings decreased between the coastal and noncoastal regions (Figure 2-6). The decrease in estimated total value between coastal and noncoastal landings is explained by lower blue crab landings by the noncoastal participants (Figure 2-6). Despite the increased cost/crab in 2015, the estimated total value was lower in 2015 for both summer and fall, than in 1997 (Figure 2-6). The lower estimated total value in 2015 is explained by the lower estimated crab landings in 2015 (Figure 2-6).

Discussion

Blue crab recreational fishing is allowed in South Carolina, but the fishery is only intermittently monitored through fisheries dependent studies like Low 1998 and this 2015 survey. In contrast, the SC DNR has commercial landings and a rough catch per unit effort of blue crabs through individual “trip tickets” that commercial dealers must complete. This project updated the state-wide recreational blue crab catch and compared it with similar historical data from 1997 using overall fishing effort and individual catch per unit effort. Our fisheries-dependent survey of recreational license holders throughout South Carolina revealed trends in recreational fishing for blue crab, some in contrast to what had been observed in 1997 (Low 1998). Both the current and historical surveys showed higher blue crab fishing activity from residents of coastal counties compared to noncoastal counties, as was expected. However, there were 1.87 times more crabbers fishing in summer 2015 than in 1997 (30,903 vs 16,449) and 2.4 times more fishing in fall 2015 (36,538 vs. 15,117). Shifts in crabbing location preference were observed between 1997 and 2015, with the 2015 crabbers preferring docks and bridges over boats, whereas boats were the preferred method of crabbing in 1997. In terms of gear type, there was an increase in the relative activity of crabbers who fished using drop net in 2015, while the use of pots declined from the 1997 survey. Despite fishing effort increasing substantially in 2015, estimated total landings decreased by 65% in summer and 62% percent in fall. The increase in estimated crabbers supported our alternative hypothesis that there would be an increase in the fishery due to population growth in the coastal counties, however, rejects the latter part of the hypothesis which suggested that the increased growth in the fishery would result in higher recreational landings for 2015. The 2015 survey illuminates an interesting issue in the fishery, such that there are more potential crabbers in the fishery, but both recreational relative crabbing participation and recreational landings have declined over the past 18 years.

In the 2015 survey, noncoastal counties had higher return rates than the coastal counties. One of the factors contributing to the discrepancy in 2015 total returns between noncoastal and coastal counties was the original distribution of postcards mailed to each region. Only 25% of the postcards were mailed to the non-coastal regions, while 75% were mailed to the coastal regions. Another study, which conducted intercept and telephone surveys of all license holders in coastal counties in Virginia and Maryland, found that a very small percentage (<5%) of the interviewee's owned waterfront property (Miller et al. 2000). However, Ashford et al. (2010) observed that waterfront households in Maryland in 2001 caught similar total numbers of blue crabs each month using their private docks than non-waterfront recreational fishers, but had to make substantially more trips to do so. This is supported by the idea of non-waterfront recreational anglers traveling to relatively more productive fishing spots, where either personal knowledge or word-of-mouth reports indicated higher crab catch rates at these locations. This resulted in CPUE of waterfront households being 74% less than that of non-waterfront households (Ashford et al. 2010). Additionally, not all recreational license holders in South Carolina participate in recreational crabbing; there are many other enigmatic target species like cobia, red drum, and sea trout. Those who do not participate in the crabbing fishery may not respond if asked about their crabbing behaviors due to lack of interest in the fishery, thus, overall participation rates may be lower than we observed. The non-coastal county total response was low; to increase non-coastal participation in future studies, a larger percentage of the postcards should be mailed to those counties.

The shifts observed in crabbing location preferences are likely a direct result of a legislative change in the recreational fishery in 2010. Prior to 2010, only anglers fishing from boats were required to have a recreational license, after the legislation, all anglers (shore-based and boat-based) were required to have a recreational license. Therefore, the Low (1998) survey was only surveying boat anglers, while our survey encompassed crabbers utilizing both boat and shore based fishing techniques. This shift in legislation could explain why pots were still predominantly reported as the most used gear type, but also explain the increase of participants who reported using drop nets. Additionally, a decrease in participants who reported using handlines. Due to the natural environmental limitations of certain crabbing locations, one gear type can be better suited for a crabbing location over another. In 2015, there was a predominant shift towards using banks and beaches more frequently than boats, but docks and bridges were the most highly utilized crabbing locations. Crabbers who reported using docks have a wider variety of gear types available to them; they can hand line, drop net, or set pots off the dock. Miller et al. (2000) found that most Virginia and Maryland waterfront property offers access to the fishery via a dock or pier, which is most suited to set pots from or dock a boat. This shift from boats to docks observed in 2015 may explain why most participants favored crab pots over the other gear types. The use of docks also explained the increase in crabbers who used drop-nets, as drop-nets are more likely to be used at docks or bridges (personal observations). An alternative hypothesis suggests the effort involved with those who fish using chicken-necks (i.e. have no dock access), is directly correlated to word-of-mouth catch rates. If catch rates are low, and this information is spread by word of mouth, then the crabbers who expend the most effort crabbing (those who use chicken-necks), will not go to the extra trouble of scouting out remote fishing locations if they know the reward of catch is low. Drop-nets and pots dominated the New Jersey fishery as well when it was surveyed in 2005 (Muffley et al. 2007). In Maryland and Virginia, where other gear types are available to the recreational fishery, hook and line was the dominant gear type used, followed by crab pots in a survey from 1999 (Miller et al. 2000). It should be noted that there are regional nuances in gear types. A New Jersey collapsible crab trap is very similar in design to the South Carolina drop-net. In Maryland and Virginia, hook and line is a heavily used gear type (Miller et al. 2000), but according to the 2015 and 1997 surveys South Carolina, was not a significant gear type in the South Carolina recreational fishery. Maryland and Virginia recreational crabbers can fish using trotlines, while trotlines are allowed in SC (section 50-5-505), they are not a significant gear in the South

Carolina fishery. Despite these available gear types, pots are either the preferred gear type or the second most preferred throughout the Atlantic east coast. Therefore, the differences in estimated catch cannot be attributed solely to the catch efficiency of the varying regional gear types.

The estimated recreational effort increased in 2015 from 1997and is partly explained by the population increase. Another likely factor is that South Carolina did not require a recreational fishing license in 1997 for fishing crabs or shrimp (David Whitaker pers. comms.); as such, numbers of licensed respondents increased for that reason alone, but also, the percentage of those crabbing may be related to the change in licensing requirements. However, the total recreational blue crab catch estimate decreased in 2015, despite an increase in effort (through growth of the numbers of fishermen) and a significant increase the sampling universe. In July and August 2015, 146,435 trips were made by an estimated 30,903 crabbers, with an estimated total catch of 251,477 crabs. In July and August 1997, it was estimated that 16,449 crabbers had an estimated total catch of 1,001,800 (Low 1998) or nearly four times as many crabs. Comparing our study to other states along the east coast produced a similar result. In New Jersey in 2007, there was an estimated 202,000 recreational crabbing trips taken, with a recreational harvest of 1.92 million crabs in July and August (Muffley et al. 2007).

Our findings, like those of New Jersey, suggest the crab resource in 2015 is not as abundant as it once was in previous years. This evidence is supported by a decrease in both the fisheries-independent (trawling and potting) and dependent sampling (landings summaries) in the state since the early 2000s (SC DNR OFM) and Crustacean Monitoring and Research Section). Much of that decline has been attributed to drought conditions in the period from 1999 to 2012. Although landings returned to pre-drought levels in 2011 and 2012, the past four years (2013-2016) have demonstrated no significant improvement in blue crab abundance (SCDNR Crustacean Monitoring and Research Section). Similar trends of decreased landings of blue crabs have been reported along the Atlantic coast, from the Chesapeake Bay through Florida (D. Whitaker, SCDNR pers. comm.). While fishery pressure may contribute to the decline (Lipcius and Stockhausen 2002; Carver et al. 2005), a universal decline throughout the east coast in crab stocks as indicated by both fishery dependent and independent data suggests that a largescale factor or factors is influencing blue crab populations. Such factors are likely to be environmentally related such as rainfall patterns, temperature, or possibly oceanic wind and water circulation patterns which may affect megalopal recruitment mechanisms. Therefore, the decline in landings in South Carolina is likely only partly explained by the changes in fishing effort. A large-scale study of all factors throughout the species range is needed to tease out the most significant factors related to blue crab abundance and harvests.

In the 1997 and 2015 South Carolina surveys, recreational blue crab catch was converted to pounds to estimate how much the recreational sector contributed to the overall take of blue crab. The recreational catch accounted for 8% in summer (July and August) and 7% in fall September and October), respectively, of the total South Carolina landings (recreational and commercial combined). The last state-wide assessment of the impacts of recreational blue crab fishing was completed in 1997 by the SC DNR Office of Fisheries Management, before the drought, and it was estimated that the recreational catch contributed between 21 and 28% of the total catch (both commercial and recreational) in South Carolina (Low 1998) and because these estimates did not include shore-based anglers in the sampling universe, they may have slightly underestimated the recreational harvest. In 2015, there was a 65% decrease in percent reduction of overall catch (compared to 1997) for the summer and a 62% decrease for the fall. These results refute our alternative hypotheses of the recreational fishery accounting for 30-35% of the commercial fishery based upon observed growth in the fishery.

Changes in climate, fishing pressure, and population shifts may be explanatory variables as to why the blue crab population has declined over the years. Fishing pressure in combination with changes in environmental conditions likely related declines in rainfall and runoff (Childress 2012), and perhaps changes in nearshore ocean circulation which would affect megalopal recruitment (Colton et al. 2014) are decreasing blue crab abundance throughout the Southeastern United States. Blue crabs rely heavily on salinity cues for habitat selection; periods of long-term drought adversely influence the salinity of their ecosystems, thus potentially contributing to a decline in the regional population (Childress 2010). With a lack of rainfall, the more valuable, larger males move above the mandated no-fishing line in search of fresher water, while the sponged female crabs stay in the higher salinities waters to spawn (Van Den Avyle et al. 1984; Archambault et al. 1990). Many crab fishermen believe the decrease in the catch is directly related to the movement of males up river to follow that salinity wedge. While the SC DNR fisheries independent catch data corroborates what the fishermen are also observing, i.e. a decrease in crab abundance, it is unknown whether this decrease is due to the complete absence of large blue crabs or just a shift in the habitat of these preferred individuals. Another cause of shifting populations could be due to changes in the path of the Gulf Stream (Colton et al. 2014). These changes in the path of the Gulf Stream were used to explain the northward distribution of silver hake (*Merluccius bilinearis*) (Colton et al. 2014), and in conjunction with population dispersal mechanisms and behavioral patterns in response to winter temperatures (overwintering) potentially explain some of the abundance variability observed throughout the east coast population (Colton et al. 2014).

Overall, this study provided updated information as to the impact and effort of recreational fishing. Additionally, this study attempted to standardize the blue crab recreational fishing surveys for South Carolina. Long periods of time between surveys are not beneficial in uncovering trends in catches, much less attributing those trends to causes. More frequent surveys, perhaps annual online surveys, could provide more consistent results that would be linked to potential causative factors. This could be especially useful years that receive extreme weather events tied to climate change (i.e. hurricane conditions, drought, increased rainfall, etc.) or economic fluctuations. It would also be useful to compare seasonal and annual changes in recreational fishing pressure to reveal temporal patterns along the coast. Further research in South Carolina is needed to understand the relative abundance and distribution of blue crabs at different life history stages and to determine how environmental factors drive populations in South Carolina. Large sample sizes of blue crab and long-term data sets are needed to account for inter- and intra-annual variability in the data due to environmental factors. Such research will serve to improve our understanding of both inter- and intra-annual fluctuations in blue crab abundances, their recent decline, and the interactions between environmental stressors and fishery pressures on the blue crab.

Tables and Figures

Table 2-1. Numbers of South Carolina saltwater recreational license holders separated by county and total number, and percentage of total that were surveyed during the summer and fall of 2015. The counties are separated into coastal (5-7) and noncoastal (1-4) groupings. Only South Carolina residents were surveyed and license type surveyed include temporary, annual, and lifetime.

					September		November	
	Region	**County**	**Total licenses**	**% of total**	**Total sent**	**% of total**	**Total sent**	**% of total**
Coastal	5	Allendale	594	0.42	39	0.52	39	0.52
	5	Bamberg	1046	0.73	65	0.87	63	0.84
	5	Beaufort	16178	11.33	855	11.38	855	11.39
	5	Colleton	4622	3.24	249	3.32	249	3.32
	5	Hampton	2163	1.51	119	1.58	119	1.59
	5	Jasper	2231	1.56	117	1.56	115	1.53
	6	Berkeley	15609	10.93	798	10.62	798	10.63
	6	Charleston	36978	25.89	1931	25.71	1931	25.72
	6	Clarendon	2546	1.78	129	1.72	129	1.72
	6	Dorchester	10340	7.24	507	6.75	507	6.75
	6	Orangeburg	4805	3.36	262	3.49	262	3.49
	7	Dillon	1681	1.18	102	1.36	102	1.36
	7	Florence	8067	5.65	445	5.92	445	5.93
	7	Georgetown	9419	6.6	483	6.43	483	6.43
	7	Horry	22100	15.48	1175	15.64	1173	15.63
	7	Marion	1877	1.31	100	1.33	102	1.36
	7	Williamsburg	2544	1.78	135	1.8	135	1.8
		TOTAL	**142800**		**7511**		**7507**	
Noncoastal								
	1	Abbeville	1560	1.32	19	0.76	18	0.72
	1	Anderson	8053	6.81	152	6.11	156	6.26
	1	Edgefield	1167	0.99	25	1	25	1
	1	Greenville	12166	10.28	280	11.25	278	11.15
	1	Greenwood	2928	2.48	85	3.42	84	3.37
	1	Laurens	3291	2.78	58	2.33	58	2.33
	1	Mc Cormick	843	0.71	19	0.76	20	0.8
	1	Newberry	2316	1.96	59	2.37	60	2.41
	1	Oconee	4624	3.91	97	3.9	99	3.97
	1	Pickens	4742	4.01	100	4.02	104	4.17
	1	Saluda	1069	0.9	12	0.48	13	0.52
	2	Cherokee	2142	1.81	52	2.09	51	2.04
	2	Chester	1630	1.38	39	1.57	39	1.56
	2	Fairfield	1259	1.06	34	1.37	33	1.32
	2	Lancaster	2419	2.04	54	2.17	55	2.21
	2	Spartanburg	9583	8.1	213	8.56	211	8.46
	2	Union	1529	1.29	23	0.92	23	0.92
	2	York	7563	6.39	161	6.47	158	6.34
	3	Aiken	6901	5.83	133	5.34	137	5.49
	3	Barnwell	1757	1.49	42	1.69	41	1.64
	3	Calhoun	1071	0.91	16	0.64	15	0.6
	3	Lexington	13544	11.45	275	11.05	276	11.07
	3	Richland	11182	9.45	229	9.2	225	9.02
	4	Chesterfield	1748	1.48	32	1.29	35	1.4
	4	Darlington	3606	3.05	83	3.33	82	3.29
	4	Kershaw	3490	2.95	57	2.29	57	2.29
	4	Lee	753	0.64	14	0.56	14	0.56
	4	Marlboro	1292	1.09	27	1.08	28	1.12
	4	Sumter	4065	3.44	99	3.98	99	3.97
		TOTAL	**118293**		**2489**		**2494**	
Combined		**TOTAL**	**261093**		**10000**		**10001**	

Table 2-2. Return data contingency table of the G2 scores, df, and p-values from a 3-way contingency test. The source accounts for the variables year (2015, 1997) and season (summer, fall), testing the return rates by region (coastal, noncoastal).

Source	G^2	df	P
Year	25.22	1	<.0001
Season	1.12	1	0.2899
Year x Season	111.08	4	<.0001

Table 2-3. A general linear model of South Carolina recreational license holders testing the influence of year, season, and region on crabbing activity. The fixed variables correspond to the survey year (1997 or 2015), the region (coastal or noncoastal), the season (summer or fall), and the type (crabber or noncrabber).

Variables	z value	Pr(>|z|)	Significance
2015	-10.823	< 2e-16	***
Summer	-5.162	2.45E-07	***
Noncoastal	-19.511	< 2e-16	***
Noncrabber	17.158	< 2e-16	***
2015 : Summer	8.839	< 2e-16	***
2015 : Noncoastal	3.57	0.00036	***
2015 : Noncrabber	9.062	< 2e-16	***
Noncoastal : Noncrabber	6.577	4.80E-11	***
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1			

Table 2-4. Distribution of South Carolina saltwater license holder population and sample population. The area of residence is coded (1-7) with noncoastal counties (1-4) and coastal counties (5-7). The “Licensed Population” refers to all recreational saltwater license holders, and the “Sampled Population” is the number of individuals that were sent a postcard. “Non-crabbers” reported no crabbing activity, while “Crabbers” reported crabbing activity. “Total Returns” is the sum of postcards returned. The “2015 % Response Rate” is the proportion of surveys returned, and the “2015 % Crabber” is the proportion of those who reported crabbing activity. The “1997 % Response Rate” is the proportion of surveys returned, and the “1997% Crabber” is the proportion of those reported crabbing for the Low (1998) study.

Area of Residence	Licensed Population	Mailing Cohort	Sampled Population	Non-crabber	Crabber	Total Returns	2015 % Response Rate	2015 % Crabber	1997 % Response Rate	1997 % Crabber
1	42,759	Summer	906	160	7	167	18.4	4.2	33.3	20.6
		Fall	915	131	11	142	15.5	7.7	35	24.3
		Combined	1,821	291	18	309	17	6	34.4	22.9
2	26,125	Summer	576	94	1	95	16.5	1.1	26.4	15.4
		Fall	570	82	10	92	16.1	10.9	29.2	20.6
		Combined	1,146	176	11	187	16.3	6	28	18.6
3	34,455	Summer	695	112	9	121	17.4	7.4	30.2	24.5
		Fall	694	105	19	124	17.9	15.3	29	26.8
		Combined	1,389	217	28	245	17.6	11.4	29.5	25.8
4	14,954	Summer	312	46	1	47	15.1	2.1	25.3	12.5
		Fall	315	47	3	50	15.9	6	18.7	11.3
		Combined	627	93	4	97	15.5	4.1	21.3	11.9
5	26,834	Summer	1,444	167	53	220	15.2	24.1	27.4	40.3
		Fall	1,440	167	53	220	15.3	24.1	26	35.6
		Combined	2,884	334	106	440	15.3	24.1	26.6	37.5
6	70,278	Summer	3,627	423	105	528	14.6	19.9	29.3	30.8
		Fall	3,627	390	86	476	13.1	18.1	29.4	28.8
		Combined	7,254	813	191	1,004	13.8	19	29.4	29.6
7	45,688	Summer	2,440	306	42	348	14.3	12.1	27.8	31.2
		Fall	2,440	314	39	353	14.5	11	28.3	27.5
		Combined	4,880	620	81	701	14.4	11.6	28.2	28.9
Totals										
Noncoastal (1-4)	**118,293**	**Combined**	**4,983**	**777**	**61**	**838**	**16.6**	**6.8**	**28.3**	**19.8**
Coastal (5-7)	**142,800**	**Combined**	**15,018**	**1767**	**378**	**2,145**	**14.5**	**18.2**	**28.1**	**32**

Table 2-5. A general linear model of South Carolina recreational license holders testing the influence of year, season, region, and their interactions on preferred crabbing location. The fixed variables correspond to the year which the postcard was received (1997 or 2015), the region (coastal or noncoastal), the location where crabbing occurred (boat, dock/bridge, bank/beach), and the season (summer or fall).

Variables	z value	Pr(>|z|)	Significance
2015	-2.329	0.01988	*
Noncoastal	-7.489	6.93E-14	***
Boat	8.203	2.35E-16	***
Dock	8.203	2.35E-16	***
2015 : Noncoastal	1.733	0.08312	.
Summer : Noncoastal	-3.346	0.00082	***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1			

Table 2-6. A general linear model of South Carolina recreational license holders testing the influence of year, season, region, and their interactions on preferred gear type. The fixed variables correspond to the year which the postcard was received (1997 or 2015), the region (coastal or noncoastal), the type of gear used (pot, handline, dropnet), and the season (summer or fall).

Variables	z value	Pr(>|z|)	Significance
Noncoastal	-6.378	1.79E-10	***
Handline	7.697	1.39E-14	***
Pot	11.999	< 2e-16	***
2015 : Summer	4.786	1.70E-06	***
2015 : Noncoastal	-1.95	0.05115	.
2015 : Handline	-5.97	2.37E-09	***
2015 : Pot	-5.369	7.92E-08	***
Summer : Noncoastal	-2.625	0.00867	**
Summer : Pot	-2.335	0.01953	*
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1			

Table 2-7. Comparison between the recreational effort expansion for hard blue crab catch calculated from the 1997 and 2015 surveys and separated by area of residence and season. Area of residence includes noncoastal (1-4) and coastal counties (5-7).

	Area of Residence	2015 Estimated Crabbers	1997 Estimated Crabbers	Responded	2015 $\sum$Catch	2015 $\sum$Trips	2015 Average $\left(\frac{Trips}{Crabber}\right)$	2015 Estimated Total Trips	2015 Average Crabs/Trip	$\frac{Crab/Trip}{Respondent}$	2015 $\sum\frac{Crabs}{Trip}$	2015 CPUE	2015 Estimated CPUE	2015 Estimated Total Catch	1997 Estimated Total Catch
	SUMMER														
	1	1,792	561	7	60	14	2	3,585	4.29	0.61	24.03	3.43	12,307	15,363	22,258
	2	275	275	1	6	2	2	550	3	3	3	3	1,650	1,650	14,608
	3	2,563	1,628	9	46	18	2	5,126	2.56	0.28	35.87	3.99	20,426	13,099	54,296
	4	318	311	1	2	2	2	636	1	1	1	1	636	636	20,352
	5	6,465	4,060	53	455	343	6.47	41,837	1.33	0.03	30.55	0.58	24,114	55,498	323,400
	6	13,976	6,885	105	770	488	4.65	64,954	1.58	0.02	193.2	1.84	119,514	102,489	416,077
	7	5,514	2,729	42	435	166	3.95	21,794	2.62	0.06	165.57	3.94	85,914	57,110	150,809
Totals	Noncoastal Total	4,948	2,775	18	114	36	2	9,896	3.17	0.18	63.90	3.55	35,131	31,337	111,514
	Coastal Total	25,955	13,674	200	1660	997	5	129,386	1.66	0.01	389.32	1.95	251,860	215,427	890,286
	Combined Totals	30,903	16,449	218	1774	1033	5	146,435	1.72	0.01	453.22	2.08	304,434	251,477	1,001,800
	FALL														
	1	3,312	662	11	89	31	2.82	9,335	2.87	0.26	39.25	3.57	33,306	26,800	40,504
	2	2,840	368	10	91	34	3.4	9,655	2.68	0.27	46.06	4.61	44,470	25,841	26,583
	3	5,279	1,781	19	180	44	2.32	12,226	4.09	0.22	66.92	3.52	43,059	50,015	98,804
	4	897	281	3	22	6	2	1,794	3.67	1.22	14.33	4.78	8,574	6,580	37,034
	5	6,465	3,586	53	517	333	6.28	40,617	1.55	0.03	127	2.4	97,330	63,060	307,493
	6	12,697	6,438	86	729	389	4.52	57,433	1.87	0.02	250.16	2.91	167,064	107,632	472,354
	7	5,048	2,001	39	305	133	3.41	17,214	2.29	0.06	148.65	3.81	65,611	39,475	97,822
Totals	Noncoastal Total	12,328	3,092	43	382	115	3	32,970	3.32	0.08	166.56	3.87	127,708	109,519	202,925
	Coastal Total	24,210	12,025	178	1551	855	5	116,290	1.81	0.01	525.81	2.95	343,520	210,953	877,669
	Combined Totals	36,538	15,117	221	1933	970	4	160,370	1.99	0.01	692.37	3.13	502,424	319,584	1,080,594

Table 2-8. Estimated total recreational catch in pounds in 1997 and 2015 based on survey responses. The "Estimated Total Recreational Catch" is the estimated recreational catch in hard crabs, which was calculated from estimated crabbers. The "Commercial Harvest (lbs)" is the commercial landings data in hard crabs, from 1997 and 2015. The "Percent of Total Catch" is the percent recreational catch, from the total landings (estimated recreational and commercial harvest). There is no commercial crabbing in the noncoastal zones (1-4); thus, the data values reported were null, represented by (-).

Area of Residence	1997 Estimated Total Recreational Catch (lbs)	1997 Commercial Harvest (lbs)	1997 Percent of Total Catch	2015 Estimated Total Recrational Catch (lbs)	2015 Commercial Harvest (lbs)	2015 Percent of Total Catch	Percent Reduction of Overall Catch from 1997 to 2015
SUMMER							
1	8,903	-	-	1,425	-	-	-
2	5,843	-	-	935	-	-	-
3	21,718	-	-	3,475	-	-	-
4	8,141	-	-	1,303	-	-	-
5	129,360	437,990	23%	20,698	287,462	7%	-71%
6	166,431	573,927	22%	26,629	352,440	7%	-69%
7	60,324	478,988	11%	9,652	148,665	6%	-45%
Total	400,720	1,490,905	21%	64,115	788,567	8%	-65%
FALL							
1	16,202	-	-	2,592	-	-	-
2	10,633	-	-	1,701	-	-	-
3	39,522	-	-	6,323	-	-	-
4	14,814	-	-	2,370	-	-	-
5	122,997	1,078,977	10%	19,680	357,091	5%	-49%
6	188,942	581,149	25%	30,231	396,485	7%	-71%
7	39,129	100,768	28%	6,261	104,611	6%	-80%
Total	432,238	1,760,894	20%	69,158	858,187	7%	-62%
Combined Total	832,958	3,251,799	20%	133,273	1,646,754	7%	-63%

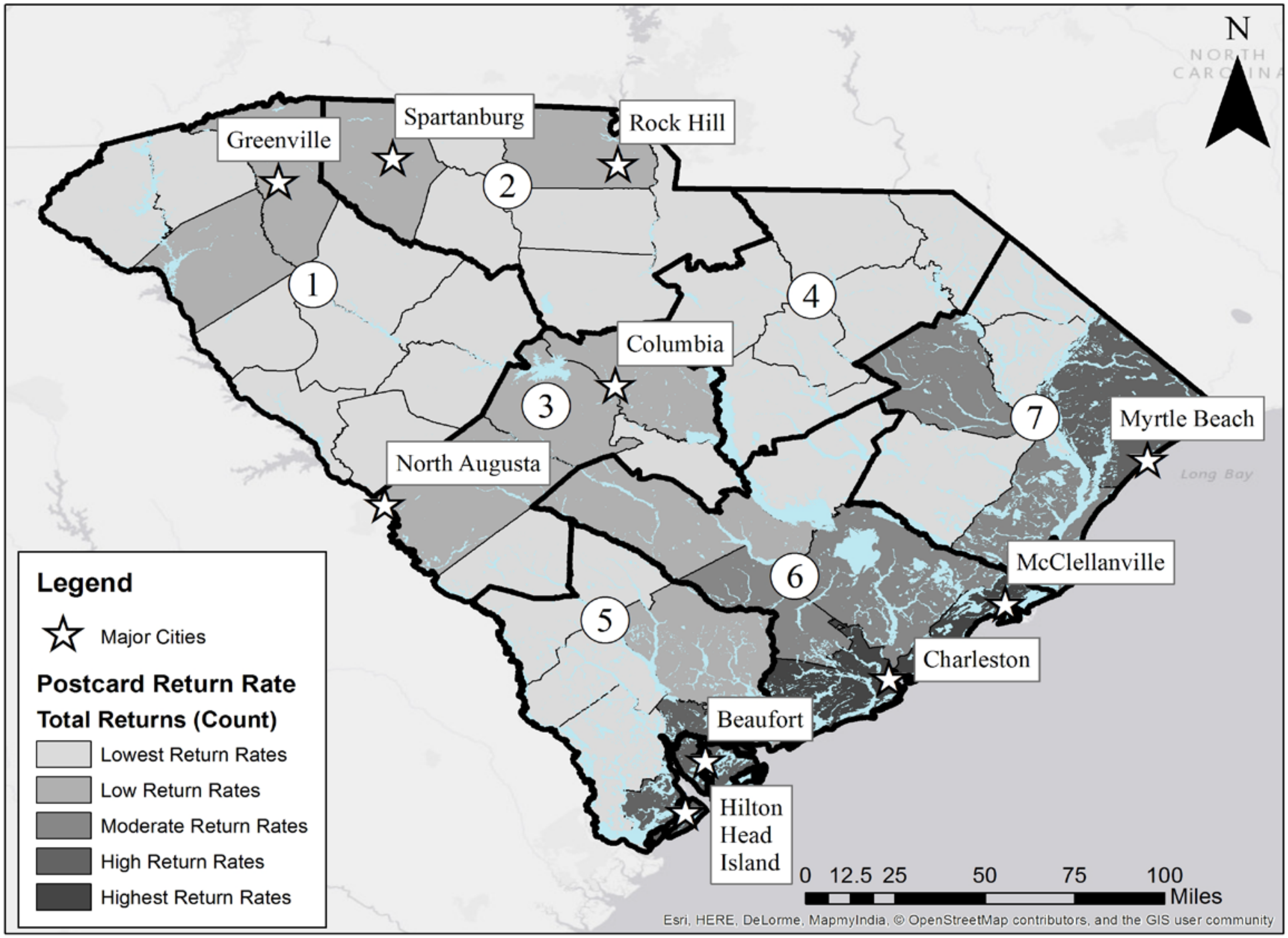

Figure 2-1. The state of South Carolina, divided into coastal (5,6,7) and noncoastal (1,2,3,4) reporting regions for both the 1997 and 2015 surveys, displaying 2015 return rates by individual counties within reporting regions combined over summer and fall.

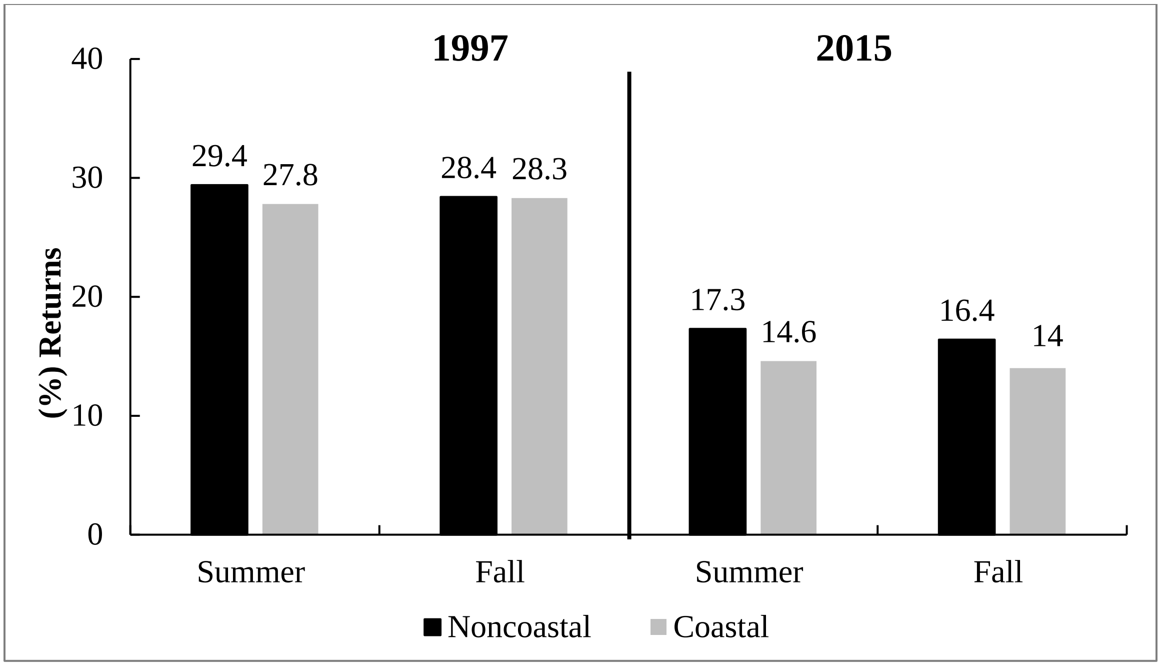

Figure 2-2. Fishery dependent survey return rate for recreational license holders. Coastal and noncoastal South Carolina counties are separated by either the September mail-out ("Summer") or November mail-out ("Fall") for the Low (1998) survey and the 2015 survey.

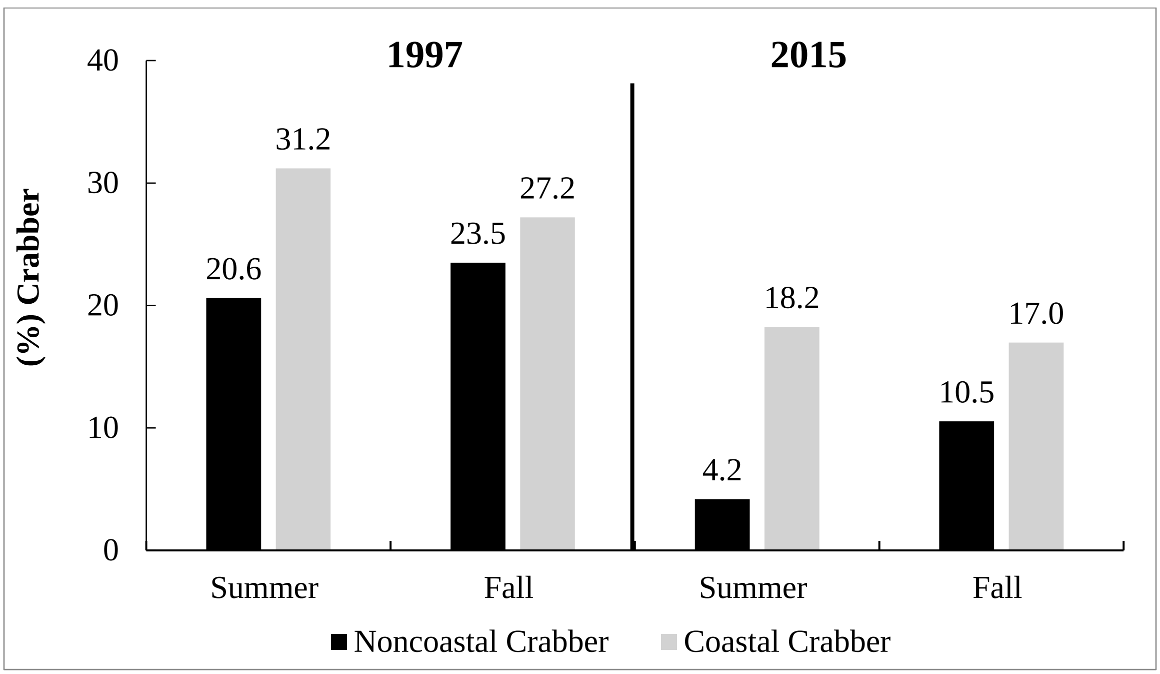

Figure 2-3. Fishery dependent survey participation rate for recreational license holders that reported crabbing activity. Coastal and noncoastal South Carolina counties are separated by either the September mail-out ("Summer") or November mail-out ("Fall") for the Low (1998) survey and the 2015 survey.

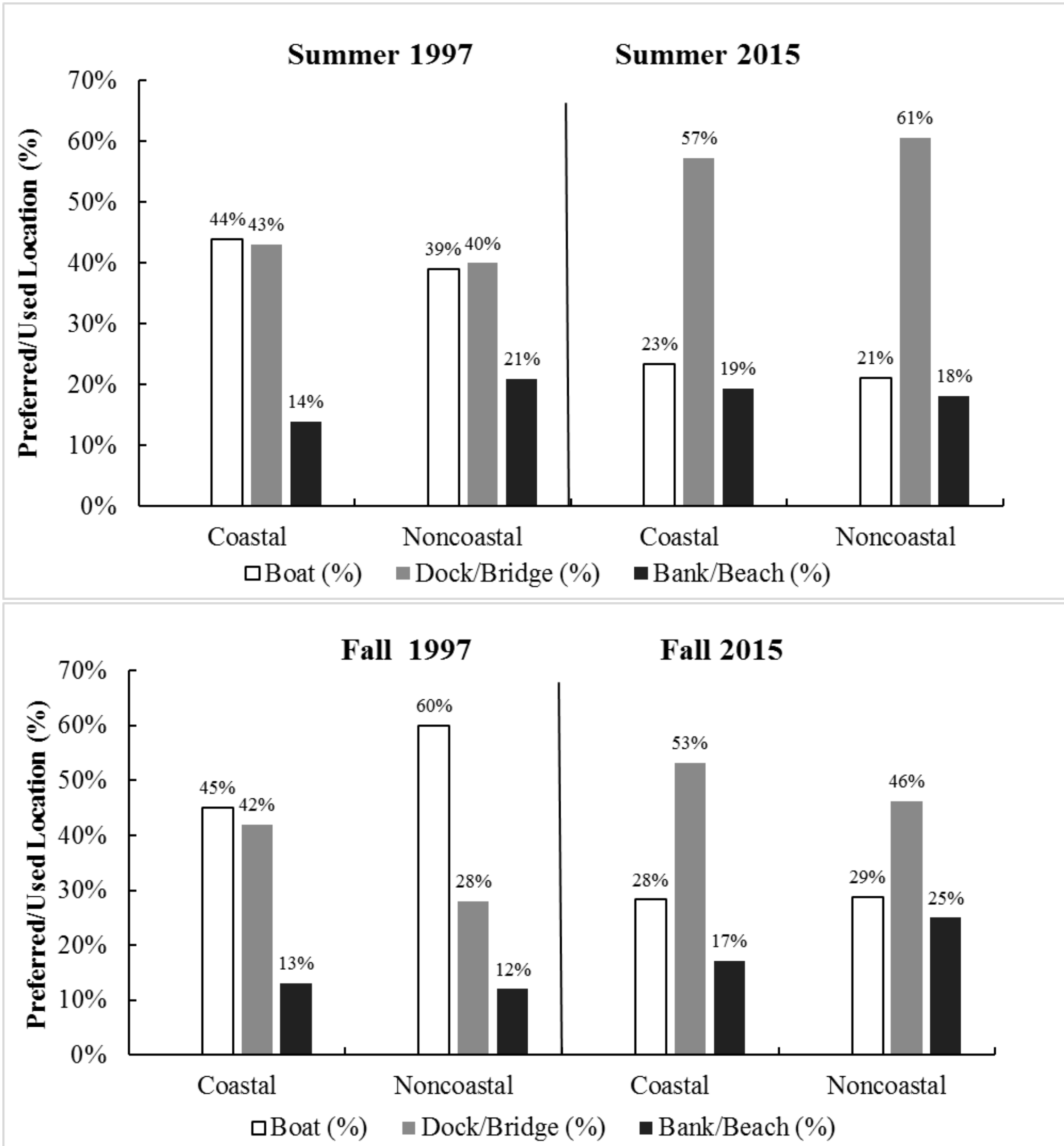

Figure 2-4. Fishery dependent survey response rate for South Carolina recreational license holders that reported crabbing activity by location crabbing occurred. Coastal and noncoastal counties are separated by season (Summer or Fall) and survey (1997 or 2015). Numbers above the bars indicate percentage of respondents who actively crabbed at respective locations.

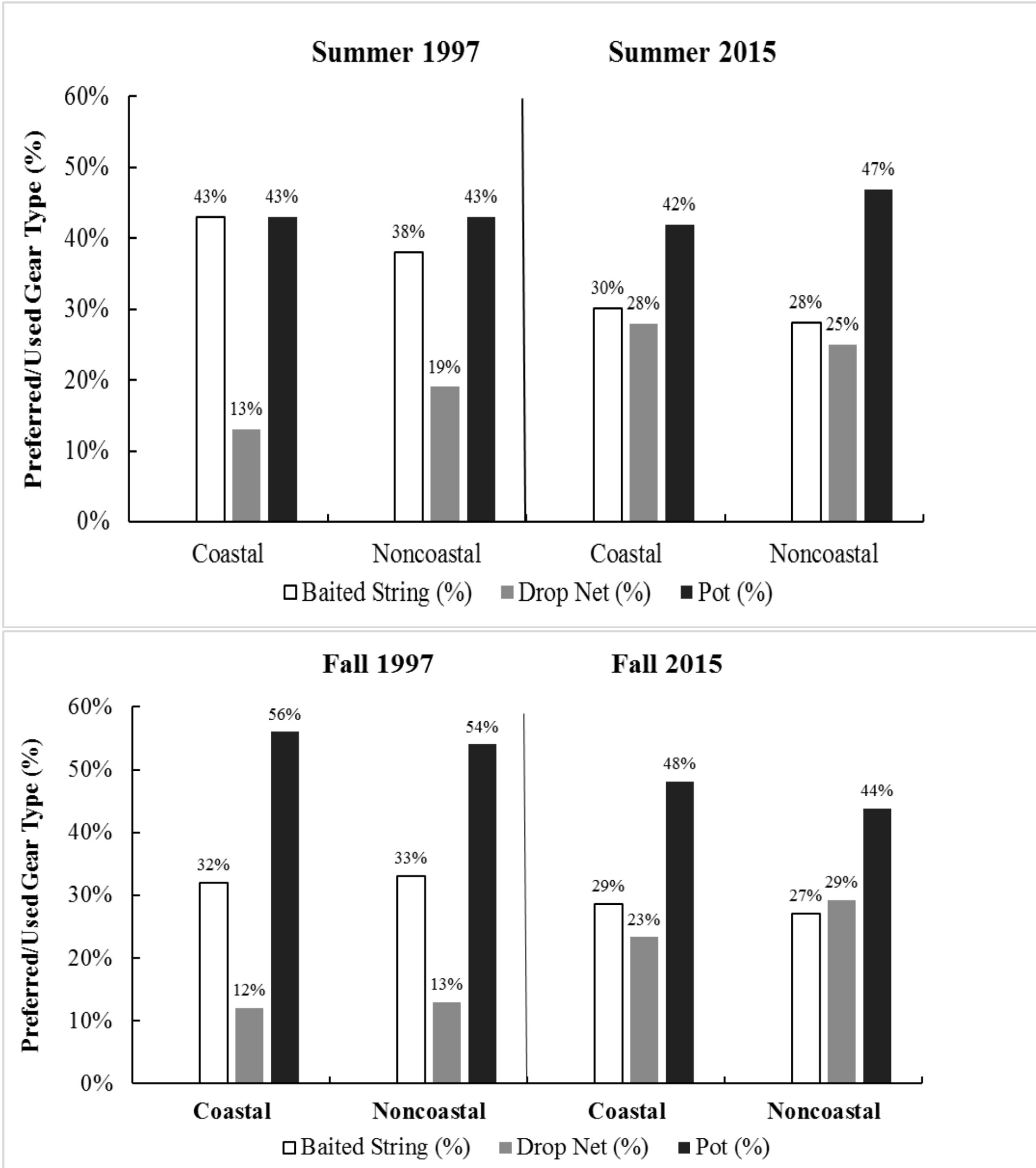

Figure 2-5. Fishery dependent survey response rate for South Carolina recreational license holders that reported crabbing activity by gear type used. Coastal and noncoastal counties are separated by season (Summer or Fall) and survey (1997 or 2015). Numbers above the bars indicate percentage of respondents who utilized the corresponding gear type.

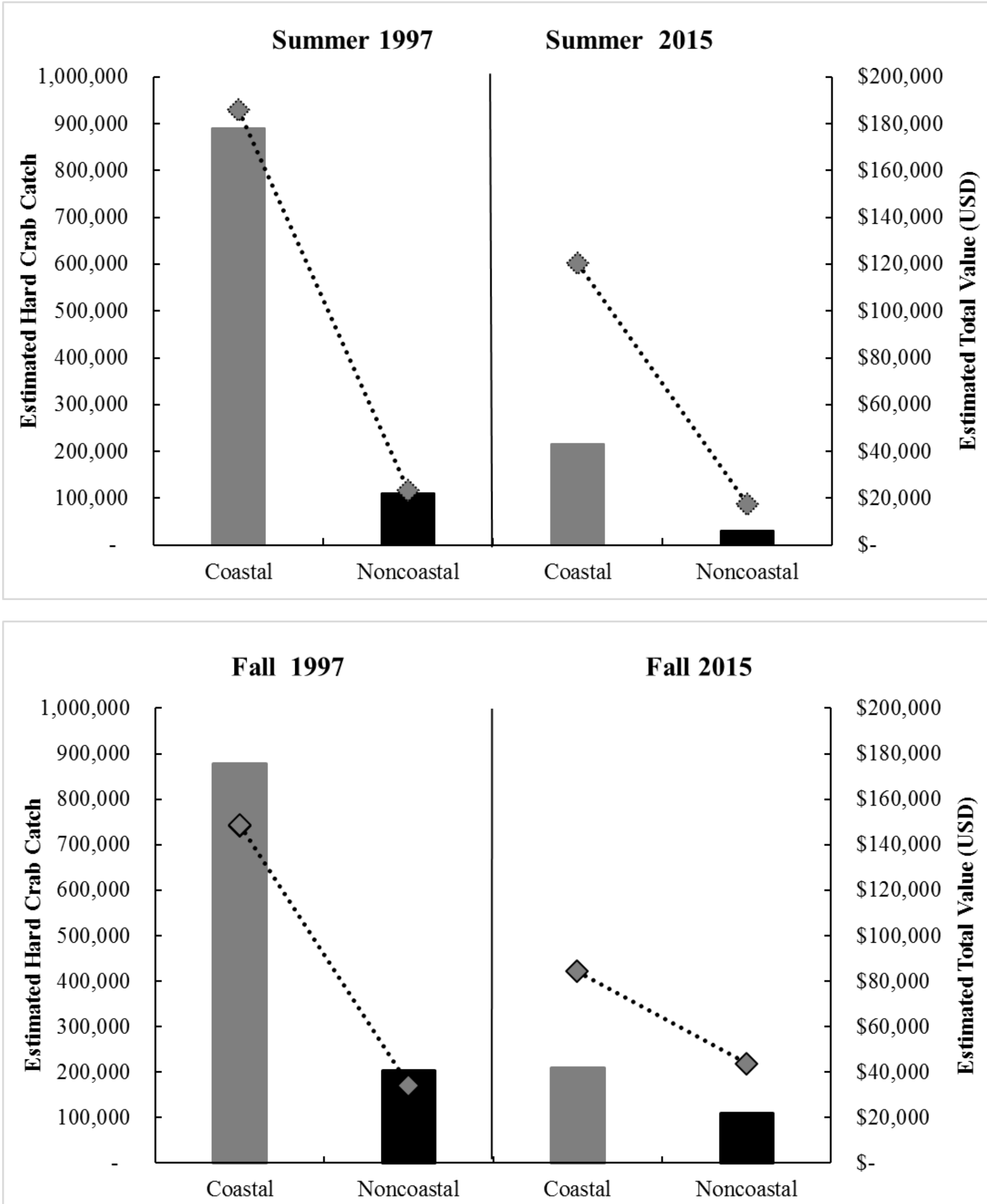

Figure 2-6. The recreational estimated catch of the coastal and noncoastal counties of South Carolina separated by season (Summer or Fall) and survey (1997 or 2015). The dashed line represents the estimated total value of the crabs, based on the individual price per crab. Estimated total values calculated based on the following prices/crab: Summer 2015 $1.40/crab and Summer 1997 $0.52/crab and Fall 2015 $1.00/crab and $0.42/crab.

3. MODELING THE EFFECT OF FRESHWATER FLOW ON THE RECREATIONAL AND COMMERCIAL BLUE CRAB FISHING EFFORT IN THE ASHLEY RIVER, SC

Introduction

The blue crab is one of the most important commercially-harvested marine species in South Carolina; historically, blue crab landings have been the most stable commercial marine landings in the state (Blue Crab Update 2007, Childress and Parmenter 2012). Although landings of blue crab have shown annual variability, the blue crab fishery has experienced a steady decline in landings since 1998 (Blue Crab Update 2007, McClellan et al. 2015, Figure 3-1). Despite the decline, the blue crab fishery is still a commercially and recreationally important species. Stock assessments are not common practice for short-lived crustacean species, so managers must rely upon annual surveys of various life stages to assess relative abundance. Crustacean fisheries are generally a small-scale production, comprised of individual watermen with small boats and individual efforts (Smith and Addison 2003); the management of the fishery is dependent on the country or state. As the scale and techniques of the crustacean fisher differ from most industrial finfish fisheries, so do the methods of assessing the respective populations. The fishery health of a finfish species can be evaluated by employing one of the various types of stock assessments (Xiao 2000), while crustacean fishery assessments consist of descriptive statistics of catch, population structure, and abundance indices

(Smith and Addison 2003). It is particularly difficult to employ an age- or growth- stock assessment to crustacean fisheries for several reasons: 1) crustaceans grow discontinuously through the molting process, 2) the temporal stages of growth are highly variable among individuals of a population, 3) crustacean ages are difficult to estimate, as they do not have otoliths or scales, 4) crustacean fisheries are managed by sex, maturity, or shell status, which would require a size based model that allows for individual variation (Bunnell and Miller 2005).

The general descriptive statistics of a fishery are beneficial to managers as an assessment of the relative and overall health of a fishery; however, an individual-based population model proves to be a useful tool in understanding the complex interactions of fishery dynamics and environmental parameters (Bunnell and Miller 2005). Individual-based models or IBMs are models that track individuals as they pass through stages in their life cycle. They differ from traditional population and fisheries models by allowing for individual variation and for estimating population level responses via the cumulative effects of the environment on individual variation (Grimm and Railsback 2005). Additionally, individual based population models can encompass the complexities of the crustacean life and growth cycle, which would otherwise be ignored by traditional models (Bunnell and Miller 2005).

The life cycle of blue crabs has three main phases: 1) a planktonic larval stage, which occurs in the open ocean; 2) a benthic juvenile stage, occurring in estuaries; and 3) a migratory adult stage, which occurs in both estuaries and the open ocean and is depending on whether the crab is male or female (Mense and Wenner 1989, Parmenter 2012, McClellan et al. 2015, Figure 3-2). In the Southeastern United States, after several passing through several larval stages in the open ocean, the blue crab settles in the salt marsh (Van Den Avyle et al. 1984, Archambault et al. 1990, Blue Crab Update 2004, Childress 2010). Juvenile blue crabs reach the South Carolina recreational and commercial legal carapace width of 127 mm (5"), measured from tip to tip of the lateral spines, after approximately 15 to 20 months (Archambault et al. 1990, Rugolo et al. 1998, Parmenter 2012). Archambault et al. (1990) found blue crab mating in the Charleston Harbor occurred throughout the spring and early summer months of June-July and into the fall during the months of August- October in lower salinity profile areas of the estuary. After mating, the females prepare to spawn by migrating towards areas of higher salinity near the mouth of the estuary, inlet or harbor; male crabs remain in the fresher water upriver (Darnell 1959, Archambault et al. 1990, Parmenter 2012, McClellan et al. 2015). In the Chesapeake Bay and South Carolina, the majority of eggs are usually hatched in the summer spawn of June-July, while a second peak spawn occurs in August (Darnell 1959, Archambault et al. 1990, McClellan et al. 2015).

The life cycle of blue crabs is influenced by salinity throughout its lifetime: survival, movement, growth, disease, mating and larval release, are all dependent on salinity cues. Shifts in freshwater discharge in estuarine systems are attributed to altered hydrological cycles due to drought and human withdrawals of surface water (Alber 2002, Knapp et al. 2008). The shifts in discharge rates and decreases in freshwater inflow lead to altered salinity profiles and higher average salinity (Childress and Parmenter 2012). While blue crabs encounter a wide range of salinities, juvenile crab survival decreases in both high and low salinity (Parmenter 2012). Furthermore, disease mortality increases with higher salinity due to increase infection by *Hematodinium* sp. (Parmenter et al.

2013) and predation mortality decreases with higher salinity (Parmenter 2012). As such, crab populations seem to thrive in intermediate salinities. A four-year field study (2008-2012) of blue crabs in the ACE (Ashepoo, Combahee, Edisto) Basin NERR found total crab abundance highest in the river with an intermediate salinity profile (Ashepoo) (Childress and Parmenter 2012). Childress used the results of this field study to forecast the influence of freshwater discharge on the population of blue crabs in the ACE Basin NERR by constructing an individual based population model (SCBCRABS) (Childress 2007, Childress 2010). This IBM model used historical data of freshwater inflow from the Edisto River to set salinity profiles for the three rivers of the ACE Basin to explore the response of crab populations to changing environmental conditions. The SCBCRABS model found a critical minimum freshwater discharge rate that was 80% of the average discharge rate (Childress and Parmenter 2012). In the model, blue crab population abundance increases in periods of drought, until reaching the minimum discharge threshold. Once below the minimum discharge threshold, the population begins to decrease (Childress and Parmenter 2012). In 2012, after a long period of intermittent drought, the IBM model suggested the ACE Basin was reaching the minimum discharge level (Childress and Parmenter 2012).

In this chapter, I extend this modeling effort to include the impacts of recreational fishing using empirical observations from the Ashley River, Charleston, SC, comprising part of the Charleston Harbor. The data collected during the field season included: fisheries independent blue crab data taken in the Ashley River, a commercial and recreational fishery simulation in the Ashley River, and biological data of the blue crab population in the Ashley river system. The purpose of this study was to answer three specific questions: How does varying competition between the recreational and commercial fisheries affect total catch? How does river flow (drought conditions, normal conditions, flooding conditions) impact the catch rates of the recreational and commercial fisheries? How could limiting female harvest influence catch rates in various simulated flow conditions (drought, normal, flooding)? First, to test fishing competition, the ratio of commercial to recreational fishing effort was varied, with no change in flow: 100% commercial pots: 0% recreational pots, 90% commercial pots: 10% recreational pots, 80% commercial pots: 20% recreational pots, 70% commercial pots: 30% recreational pots, 50% commercial pots: 50% recreational pots. Second, to investigate the impacts of river flow on catch rates, the model simulated the 80:20 commercial to recreational pot ratios while replicating drought, normal, and flooding conditions in the Ashley River. Finally, the model simulated a hypothetical management decision to close the female harvest for a full spawning closure (mid-April to late-September), a half closure (June-July), and no closure. This was crossed with flow effects (drought, normal, flood) to see the implications of management decisions in conjunction with climate variability. The results from these experiments could help to inform management and legislation about the importance of fishery closures on females during extreme periods in the hydrological cycle (drought or amplified rain events).

H_1: If the commercial fishery has a higher fishing effort than the recreational fishery, the catch rate of the commercial fishery will be higher than the recreational fishery.

H_2: If the discharge rate is in a drought simulation, the catch rate of both commercial and recreational pots will be higher than in normal or flooding conditions.

H_{3a}: Seasonal closures will have no impact on the catch rates of the commercial and recreational fisheries.

H_{3b}: Partial seasonal closures (April-May) will protect the primary spawner's of the year, and commercial and recreational fisheries catch rates will decrease initially, but not significantly, and catch rates will increase over time.

H_{3c}: Full seasonal closures (April-late September) will protect the primary and secondary spawner's of the year, and commercial and recreational fisheries catch rates will decrease significantly, and catch rates will increase over time.

Methods

Field Methods

The Ashley River, near Charleston, is indicative of both recreational blue crab fishing pressure, with both private and public dock access, and commercial blue crab fishing. As such, 10 sites along the Ashley River were selected for the field experiment portion of this study. These 10 sites are representative of a salinity gradient ranging from a minimum salinity of 0.1ppt (Site 1) to a maximum salinity of 31 ppt (Site 10) (Figure 3-3), and both a recreational (shoreline) and commercial (channel) pot was fished at each site. Environmental data (water temperature, salinity) were recorded on the days the pots were set; on the days, the pots were checked biological data (abundances of sublegal and legal, separated by sex) and environmental data were recorded. The environmental data consisted of top and bottom measurements, for analyses, bottom measurements were used as blue crabs are largely benthic organisms. The bottom salinity data from each set date were used to create an IDW (Inverse Distance Weighted) surface in ArcGIS 10.4.1.The IDW displays the averaged salinity data taken at each site for the entire sampling period, and extrapolates the data to the next known data point (or site), therefore creating a visual display based on the empirical data collected during the field component of this study (Figure 3-3). Each site was fished biweekly between May 14th and October 29th, 2015 for a total of 13 fishing days. Both shoreline(4-24ft) and channel pots (7-21ft) were baited with two large menhaden and soaked for 24 hours. As part of the data collection process, counts of commercial pots and recreational pots that were in the water, were collected on the 2nd day of each (2-day) sampling period. Commercial pots were counted between each site (10-9, 9-8, 8-7, 7-6, 6-5, 5-4, 4-3, 3-2, 2-1) by two observers, the observer counts were averaged to eliminate bias, and the average number of observed commercial pots was used for analyses. If the counts between the two observers varied more than ±3, that section of the survey was recounted for accuracy. The environmental and biological field data and the pot counts were used to establish the empirical baselines for the SCBCRABS-ASHLEY model.

Individual Based Population Model
SCBCRABS (NetLogo 4.0)

An individual based model (IBM) is a computer simulated ecosystem where an agent's, in this case an individual blue crab, life stages are tracked from when the crab enters the model as a juvenile through settlement and eventually death (Childress 2010). The IBM relies on ecological equations between environmental factors and the individual organism (in this case, a blue crab) to best predict the outcome of that individual. The more refined the relationships (equations), the more accurate the prediction output (Childress 2010). The South Carolina Blue Crab Regional Abundance Biotic Simulation(SCBCRABS)-ASHLEY model (NetLogo 4.0.5) tracks a population of blue crabs throughout the simulated habitat of the Ashley River. The SCBCRABS-ASHLEY model was developed from the SCBCRABS-ACE model and was written using the modeling platform NetLogo 4.0.5 (Appendix B). The interface of the SCBCRABS-ASHLEY model is a collection of 2,583 habitat patches representative of the saltmarsh and geomorphology of the Ashley River, consisting of three different types of patch:

open water, shallow marsh, and land (Figure 3-4.1, Figure 3-4.2). A patch is a simulated representation of the environmental conditions a blue crab may realistically encounter; the patch water quality conditions (temperature, salinity, dissolved oxygen) change according to season and spatial positioning along the model river system (Appendix B: lines 747-749). The type of habitat patch, spatial location, and depth determine the current abiotic variables for each patch. The IBM accounts for the growth, movement, disease, reproduction, natural mortality and fishing mortality. These factors are size-specific and spatially dependent on the patch where an individual crab is found (Appendix B : lines 846-861). The model tracks the survivorship or mortality of each crab, and provides updates on a weekly basis within the model. The crabs are first accounted for in the model as first stage juveniles, immigration is determined by the user, and settlement is determined by size-specific fecundity estimated as settlers per bought of reproduction (Appendix B: lines 795-809). The settlement of crabs can only occur in habitat patches (water). The SCBCRABS ecosystem abiotic data (temperature, dissolved oxygen, salinity, flow) were based on historical data (USGS gauging station 02175000, ACE-NERR station St. Pierre), and empirical data collected by Parmenter (2012) and this study. The baseline model conditions for all simulations were set as follows: initial number crabs (3000); births 4/female/brood; immigration 0 larvae/week; ratio of commercial to recreational traps 10:1; commercial trapping probability 0.5; recreational trapping probability 0.5; carrying capacity 60,000 (crabs); temperature change 0◦F; dissolved-oxygen-change 0 (Figure 3-6). SCBCRABS-ASHLEY initial set-up routine, with agents populating the “click and point” interface. Each patch color is representative of a geological feature found in the wetland area: dark green is upland, light green is wetland, dark blue is the water within the river system, orange patches with white squares are recreational crab traps, and yellow patches with circles are commercial crab traps (SCBCRABS-ASHLEY NetLogo 4.0.5**,** Appendix B). In the model, flow and fishing pressure were varied. Flow or discharge rates are expressed as a ratio difference from normal conditions. drought conditions (-30% of normal flow), normal flow conditions, and flooding conditions (+30% of normal flow). These conditions modified a historical seasonal baseline derived from the 65-year historical record of Edisto River discharge (USGS station 02175000, Appendix B: lines 854 – 857). At the beginning of this study, there were no USGS river gages in the Ashley River, but for the years when USGS gages were present in the model, the relative seasonal flow rates between the Edisto River Gage and the Ashley River Gage were significantly correlated. Flow rates in the model are a sine curve approximation of the seasonal timing of low and high flow. The flow simulations in the model are not the flow rates for either river, but rather, conservative estimates of flow rates observed in real-time. In the model, fishing was simulated by patches representing traps of either commercial pots or recreational pots (Figure 3-4.2). While each pot had a trapping probability of 0.5, as each agent moves into a patch, the model asks if the crab is a juvenile (J1-J11). If the crab is a juvenile, it is excluded from the potential of being trapped through a series of if/and statements (Appendix B: lines 863 – 902, 1035 - 1056). Trapping probabilities are created through similar logic, if an agent enters a patch, the SCBCRABS-ASHLEY model performs a series of if/and statements. The movements are dictated by time of year, sex, carapace width, and salinity, to appropriately reflect the realistic environmental conditions at that spatial and temporal location (Appendix B: lines 904 -1031). All analyses were completed using JMP®, Version *12.1.0*. SAS Institute Inc., Cary, NC, 1989-2007.

Replicating Fishery Pressures

In South Carolina, recreational fishing historically was thought to account for roughly 21-28% of the South Carolina commercial landings (Low 1998). This is comparable to a 2007 study in the Delaware Bay, where the recreational harvest was estimated at 1.92 million crabs harvested; the equivalent of 20% of the New Jersey commercial harvest in Delaware Bay during the same fishing period (Muffley et al. 2007). In a 2015 survey of the South Carolina recreational fishery, an estimated 15.9% of respondents from a survey of 20,001 participants crabbed, while the estimated recreational landings account for approximately 7% of the total commercial landings (Chapter 1, page 23). There are several justifications for altering the fishing effort of the commercial and recreational sectors: 1) to demonstrate that 1 commercial pot is not equal to 1 recreational pot due to extraneous variables such as pot interference, 2) accurately represent historical, current, and future fishing efforts, 3) investigate the impacts of varying recreational effort on the commercial sector's landings.

The SCBCRABS- ASHLEY model replicated the commercial and recreational fisheries by simulating the commercial fishery's seasonal movement of pots up and down the mid-channel of the river (Appendix B: line 1758-1827), while the recreational pots remained static in the model as if attached to shoreline docks. These spatial patterns were programmed based on field observations of commercial and recreational behaviors where mid-winter fishing occurred near the mouth of the river and mid-summer fishing near the upper legal limit. In addition to programming the movement of the respective fisheries, the model simulated varying recreational and commercial fishing pressures. The pressures were simulated with a sequence of pot ratios (100:0, 90:10, 80:20, 70:30, 50:50). In the SCBCRABS-ASHLEY the pot ratios are not a one-to-one ratio, but rather a ratio of 1 recreational pot for every 10 commercial pots. The observed frequency of commercial to recreational pots seen in the field was (90:10) (Table 2-1). All analyses were completed using JMP®, Version *12.1.0*. SAS Institute Inc., Cary, NC, 1989-2007.

River Flow and Catch Rates

River flow and the catch rates of blue crabs are correlated; when river flow is low, blue crab landings decrease in low flow rivers (Childress 2010). River flow is directly influenced by freshwater input into the system. If there is a period of drought in the hydrological cycle, there is little to no freshwater recharge occurring in the system. As such, there is an increase in salinity. A seasonal increase in salinity, due to low freshwater runoff, was observed during the field research component of this study (Figure 3-8). Blue crabs are directly impacted by these shifts in salinity (Figure 3-9; 3-10; 3-12). To evaluate the influence of varying river flow in the Ashley River system, flow conditions were adjusted in the SCBCRABS-ASHLEY Model as follows: drought conditions (-30% of normal flow), normal flow conditions, and flooding conditions (+30% of normal flow). These flow conditions modified a historical seasonal baseline derived from the 65-year historical record of Edisto River discharge (USGS station 02175000), (Appendix B: lines 854 – 857).

River Flow, Seasonal Closures, and Catch Rates

SCBCRABS-ASHLEY was programmed to incorporate several realistic anthropogenic impacts to the fishery; specifically, simulated varied flow due to an altered hydrological cycle and representative fishing pressures mimi-cking commercial and recreational fisheries. One experimental parameter which was incorporated into the model, but is not representative of an observed variable in the South Carolina blue crab fishery, is the seasonal closure of the fishery. Seasonal closures in the blue crab fishery occur in a few states on the east coast—in the form of limiting female harvest (Maryland and Virginia). For this study, the most realistic management strategy was to limit the female harvest during spawning season. In South Carolina, the females spawn from May-June and July-August; spawning can occur as late in the season as September. To assess what the population structure would look like if seasonal closure regulations were enforced, we simulated two of the most likely closures and controlled for the current management conditions of no closures. The two harvest regulations selected: a partial closure and a full closure during the spawning season. The partial closure would require the return of all females to the water for a two-month period (mid-April to mid-June) during the main spawning season. A full closure, during the entire spawning season (April to September), would require the return of all females to the water for a five-month period. We coded these regulations by prohibiting female agents (female crabs) from entering recreational or commercial traps by setting catch restrictions on the habitat patch according to the number of weeks (Appendix B: line 1105-1150). These fishing regulations were crossed with catch rates and flow to evaluate the benefits of managing a fishery undergoing environmental stressors—such as drought or flooding.

Results

Field Results

Bottom water quality data taken on the day the pots were sampled were used for analyses. No significant difference was found between shoreline and channel salinities across sites for dates (F=0.134, p= 0.7133), thus the salinities were averaged by site and date (Figure 3-9). As expected, there was an overall increase in salinities at each site over the course of the summer. However, there was a drop in the salinities for the October 15th and 29th 2015 time points (Figure 3-10). This reflects the inundation of freshwater runoff from the massive flooding event experienced in South Carolina at the beginning of October 2015.

A total of 1,173 blue crabs were caught: 580 of these in channel pots and 593 in shoreline pots. While there were significant differences in blue crab catch rates by date ($F_{(1,128)}$=5.04, p<0.0001) and site ($F_{(1,128)}$=4.65, p<0.00004), there was no significant difference found between shoreline and channel blue crab catches at each site for particular dates ($F_{(1,128)}$=3.70, p= 0.236), thus the blue crab catches were averaged by site and date (Figure 3-11). While we did see trends for blue crab sex and maturity status to be related to salinity, none of these values were significant. The data do suggest that mature females tend to move to at the lower reaches of the Ashley River, where there are higher salinities (Figure 3-11). Males and immatures of both sexes are present at all sites.

SCBCRABS-ASHLEY Results

The analysis of variance of these results is a sensitivity analysis of the parameters in the model. The ANOVA of these results is dissimilar from the field data as there are no true population parameters that are trying to be estimated through sampling. Every run of the model is a true population of a simulated world. The purpose of an ANOVA is to inform us as to which of the modified parameters has the greatest sensitivity (or effect size). All the parameters in the SCBCRABS-ASHLEY model have a significant influence on total crab numbers and explain 94.4% of the variance. Of the four main effects examined for their influence on total crab numbers, flow rate > commercial trap closure > commercial / recreational trap ratio > recreational trap closure (Table 3-2). Within the model, the crab population increased in low flow. Additionally, if both fisheries were experiencing full closures, the abundance of crabs within the model would increase.

Replicating Commercial and Recreational Fishery Pressures

To examine the relative influence of commercial versus recreational pots on the commercial catch of crabs, we conducted replicate simulations with equal numbers of pots that varied in their commercial: recreational pot ratio (50:50 70:30, 80:20, 90:10, 100:0). The 100:0 ratio was not included in the ANOVA for analyses. Not surprisingly, the number (and percent total) of crabs caught in commercial pots increased with an increasing proportion of commercial pots (Figure 3-7). However, so did the relative difference between the expected versus observed catch percent. For example, commercial pots only caught 30% (-20% from expected) of all crabs landed when they were in equal abundance with recreational pots or the (50:50%) ratio. This discrepancy was maximal at the 80:20% ratio where commercial pots only caught 42% (-38% from expected) of all crabs landed. A Tukey post-hoc comparison found that number of crabs landed by commercial pots were significantly higher only when ratios were 90:10% or greater (50:50% = 70:30% = 80:20% < 90:10%). Recreational pots outperform commercial pots in mean catch, in normal flow conditions, until the commercial to recreational ratio is 90:10. At this ratio, the commercial pots outperform the recreational pots with a mean catch of 64.26%. The pot ratio of 90:10 has the largest effect size within this model (Table 3-2), the parameter of fishing effort has a significant effect on the model R^2=0.85, ($F_{(3,16)}$ = 29.97, $p < .0001$). The empirical data on catch rates presented above indicate that relative position does not influence catch rates, but that position in the river does (Figure 3-10). The combined effect of commercial pots being less abundant and being distributed along the entire length of the model rather than being concentrated into a season-specific smaller region of the model increased the inter-pot distance and corresponding catch per trap. More pots do not equal a higher catch, this is shown in (Figure 3-11) between the 50:50, 70:30, 80:20 ratios, where the recreational pots outperform the commercial pots in terms of mean catch.

River Flow and Catch Rates

Catch rates in various states of river flow were tested with an ANOVA. Analyses were performed on the historical commercial to recreational fishing rate of 80% commercial pots to 20% recreational pots, these ratios were determined from the Low (1998) report. In a drought state, the commercial pots significantly outperformed the recreational pots in terms of percent catch $F_{(2,16)} = 16.27$, $p = 0.0004$, and a Tukey Post-Hoc Analysis found that the commercial pots performed similarly in normal, and high flow conditions (Low > Norm = High) (Table 3-3, Figure 3-12). In terms of recreational catch, an ANOVA revealed recreational pots have higher catch rates in flooding conditions $F_{(2,16)} = 16.27$, $p = 0.0004$ (Table 3-3). A Tukey Post-Hoc analysis shows that recreational pots perform just as well in high flow conditions as they do in normal flow conditions (High = Norm > Low). In both a normal state and flooding state, the recreational pots outperformed the commercial pots, but the recreational pots only significantly outperformed the commercial pots in normal flow conditions (Figure 3-12).

River Flow, Seasonal Closures, and Catch Rates

Two fully crossed ANOVAs were run to evaluate the catch rates of the 80:20 commercial to recreational fishing ratio under management regulations. In one instance, seasonal closures were applied to the commercial fishery (Table 3-4.1), and the recreational fishery was an open fishery all throughout the season. In another, seasonal closures were applied to the recreational fishery, while the commercial fishery was an open fishery throughout the season (Table 3-4.2). Both factors were crossed with flow. The commercial closures did not significantly affect the fishery $F_{(2,134)} = 6.65$, $p = 0.0035$. A Tukey Post-Hoc analysis shows commercial pots have equal catch rates with no seasonal closures and partial seasonal closures (Table 3-4.1, Figure 3-13). As expected, both simulations of no seasonal closure and partial seasonal closure had higher catch rates than a full season closure of female harvest (None = Half > Full), (Figure 3-13). When a full season closure was applied to the recreational fishery, the commercial fishery significantly outperformed the recreational fishery (Figure 3-9**).** When the recreational fishery had no seasonal restrictions and half of the season was closed, and the commercial fishery was under full seasonal closure of female harvest, the recreational fishery outperformed the commercial fishery, but not significantly (Figure 3-13).

The commercial fishery outperformed the recreational fishery when there were no restrictions on either the commercial or recreational fishery (Figure 3-9). The commercial fishery had a higher mean catch than the recreational fishery when the commercial fishery was restricted for half a season, but when the commercial fishery was restricted for a full season, with the recreational fishery under no restrictions, the recreational fishery had a higher mean catch (54.25%), but it was not significantly higher than the commercial mean catch (Figure 3-9). When the recreational fishery was restricted for half of the season, the recreational fishery had a higher mean catch (52.75%) than the commercial fishery (Figure 3-9).

Discussion

Based on previous literature and well established hypotheses, the SCBCRABS-ASHLEY model was created to simulate an altered hydrological cycle, varied fishing pressures, and alternative management strategies. Altered freshwater input and increasing fishing pressure are negatively impacting the South Carolina blue crab fishery; but, these variables are difficult to test *in-situ*. The spatially explicit SCBCRABS-ASHLEY model allows for users to parameterize abiotic factors to forecast future landings based on historical data and accounts for hypothetical variables such as management strategies. For species difficult to age due to discontinuous growth— individual based population models are a clear alternative to tradition stock-assessment techniques. This study focused on the Ashley River, SC as there was a field component which was used to validate the IBM's parameters. Using the empirical field data in combination with historical environmental data, we found the efficacy of commercial to recreational pots is not a one to one relationship. Recreational pots have higher total catch rates than commercial pots in certain environmental conditions, flow conditions significantly influence the landings of the two fisheries, and commercial pots have similar catch ratios in during a period of partial catch restriction as they would if there were no restrictions at all.

In SCBCRABS-ASHLEY, the commercial pots move linearly up and down the model following the seasonal cycle of perceived crab movement based upon catch rates. This is a simulation of what is observed in the commercial fisheries of South Carolina. Recreational pots generally are placed off private docks, or at a specific fishing location, therefore, the recreational pots are static and do not move. These specific behaviors of each fishery contribute to their relative success or failures in terms of percent catch. The commercial and recreational pot ratios were carefully selected for two reasons: 1) to mimic historical (80: 20) and observed recreational fishing effort (90: 10) and 2) to show the catch efficiencies of each respective fishery if they were fishing in equal abundance (50: 50). In the model, the 50: 50 ratio demonstrates that if commercial pots are not spatially well distributed, the commercial pots compete for finite catch against other commercial pots. At the 70:30 and 80:20 ratios, under normal flow conditions, the recreational pots had higher mean catch than the commercial pots, also suggesting competition between commercial pots. This phenomenon is known as “pot interference” (Sturdivant et al. 2010). Pot interference has been noted in other crustacean fisheries, such as lobster, but coined as “trap saturation” (Bell et al. 2001). Pot interference reduces trapping probability and decreases the efficacy of the traps, therefore, reducing the overall success of the commercial fishery. Pot interference can occur from other commercial pots or even from derelict pots “ghost pots” (Voss et al. 2015). In North Carolina, an estimated 1 million commercial crab pots are used in the fishery, with an annual loss rate of 17% (Voss et al. 2015). Therefore, the potential catch competition from both active and derelict gear is an important consideration for the commercial fishery. While date and site impacted, blue crab catch in the Ashley River, there was no significant difference in blue crab catch rates between “commercial” and “recreational” pots in the field study.

Empirical field data show the commercial to recreational fishing efforts in the Ashley River to be approximately 90:10; in the 2015 recreational survey, recreational blue crab landings only accounted for ~7% of the total blue crab landings (Chapter 1, page 25). This is a stark contrast from the historical recreational fishing estimate of ~20% (Low 1998). In a 2005 study conducted in New Jersey, the recreational catch accounts for approximately 20% of the New Jersey commercial harvest (Muffley et al. 2007). Thus, while the 90:10 ratio was observed in the field, the 80:20 ratio is more representative of the historical recreational crabbing distribution by state, along the coast. As such, the 80:20 ratio was selected for when investigating influences of flow. Flow influenced the percent mean catch of the recreational and commercial fisheries; commercial fisheries outperformed recreational fisheries in low flow conditions. Contrarily, at high flow, the recreational fishery had the higher total mean catch.

The relationship between salinity and blue crab habitat usage by sex and life stage is well documented (e.g., Tagatz 1971, Childress 2010, Parmenter 2012). Adult males are more commonly found in lower salinity water, while adult females migrate seaward and will be more abundant in intermediate and higher salinities, as spawning typically takes place in high oceanic salinities (Tagatz 1971). We also observed this pattern in the field survey, with most adult females found at the highest salinity sites throughout the season. However, during unusually high discharge rates, the movements of the population become extreme as the crabs attempt to re-equilibrate to the altered environmental conditions. While the blue crabs are physiologically suited to tolerate a wide salinity range (Ward 2012), extreme discharge rates, in our observations, led to rapid migration further downriver. Yet, there was no significant relationship between blue crab catch rates and salinity values, suggesting that other environmental variables may also be influencing blue crab habitat selection. Contrarily, during drought events, the lack of freshwater inflow can result in increased salinity in estuarine river systems (Childress 2010). In this case, blue crabs respond both behaviorally, by following the salt wedge up the tidal river, and physiologically, by performing osmoregulation in varying salinities (Ward 2012). Long-term fisheries independent surveys along the South Carolina coast, conducted by the SCDNR have shown an overall increase in salinities from 1980 to 2012 with a concurrent decrease in blue crab catch at fixed sampling location in the estuaries. This correlation suggests that reduced rainfall and river flow rates may be related to declining crab population abundance. This could potentially be explained by several mechanisms, including decreased optimal nursery habitat, negative physiological responses to higher salinity, increased disease prevalence (*Hematodinium* sp.), and declining numbers of spawners due to differential catch rates of males and females. Continued monitoring of blue crabs in the Ashley River along this salinity gradient would be helpful in interpreting how and why blue crab abundances shift.

Population abundances are directly correlated to spawning stock abundance and biomass; if the spawning stock of the population is depleted, the likelihood of successfully rebuilding the stock is low. A successful rebuilding of the stock can only occur with targeted management strategies; such as stock enhancement and protection of the spawning stock (Aguilar et al. 2008). Female blue crabs are particularly susceptible to commercial fisheries due to their migratory nature through the estuary, as they seek to mature, mate, and spawn. From 1998-2000 over 80% of the spawning stock abundance was annually depleted in the Chesapeake Bay area (Aguilar et al. 2008). To protect the spawning female stock, seasonal closures of female harvest were projected in the SCBCRABS-ASHLEY. The purpose of these projections was to estimate the most successful type of regulations for both the stock and the fishermen. The most realistic fishery closure would be a “half” seasonal closure, where there is no female harvest from mid-April to mid-June. In SCBCRABS-ASHLEY, commercial catch rates perform equally well under partial and no management structures. While some call for “spawning corridors” (Aguilar et al. 2008), perhaps an elimination of females from the harvest during known spawning periods is one alternative management solution. SCBCRABS allows managers to investigate potential impacts of regulations on commercial harvest, without being detrimental to the actual fishery. The SCBCRABS model is a powerful tool which permits managers to discuss “what-if” situations for species that are difficult to monitor or for data-limited fisheries.

The SCBCRABS model can theoretically be applied to other systems; however, to do so, one must collect the required environmental data to properly inform the model of the environmental equations (flow, temperature, salinity, dissolved oxygen). Additionally, the model interface should be spatially representative of the system it is attempting to model; therefore, any user attempting to adapt the model to a new system will need to create representative patch data which takes into account the geomorphological features of the river. This model could help managers create hypothetical environmental and regulatory situations for other river systems with an observed commercial and/or recreational crabbing fishery. One of the next steps for

SCBCRABS would be to look at a river system such as the Pee Dee River, which has extensive dam projects throughout the river, and investigate the influence of controlled flow on blue crab populations.

Tables and Figures

Table 3-1: The observed ratio between commercial and recreational pots fished in the Ashley River.

Transect	% Commercial Pots	% Recreational Pots
1-2	75%	25%
2-3	100%	0%
3-4	87%	13%
4-5	92%	8%
5-6	97%	3%
6-7	99%	1%
7-8	99%	1%
8-9	99%	1%
9-10	98%	2%
Average	94%	6%

Table 3-2: ANOVA sensitivity analysis of crab abundance in relation to flow rates, commercial: recreational trap ratios, commercial trap restrictions and recreational trap restrictions ordered from largest to smallest effect sizes.

Effect	Log worth	df	F Ratio	Prob
Flow	283.1	2	1488.1	<0.0001
Commercial restrictions	194.2	2	990.8	<0.0001
C:R trap ratio	168.9	3	113.7	<0.0001
Flow X C restrict	151.8	4	272.1	<0.0001
Recreational restrictions	140.8	2	714.7	<0.0001
Flow X R restrict	78.3	4	125.4	<0.0001
Flow X C restrict X R restrict	58.7	8	21.3	<0.0001
C:R trap ratio X R restrict	55.1	6	12.3	<0.0001
C restrict X R restrict	55.0	4	76.8	<0.0001
C:R trap ratio X Flow	46.8	6	18.6	<0.0001
C:R trap ratio X C restrict	26.5	6	25.8	<0.0001
C:R trap ratio X Flow X C restrict	24.8	12	6.6	<0.0001
C:R trap ratio X Flow X R restrict	22.6	12	3.2	0.0002
Four-way interaction	5.7	24	0.8	0.6840

Table 3-3: Sensitivity analysis ANOVAs for five measures of model population structure versus four levels of commercial: recreational fishing effort 90:10%, 80:20%, 70:30%, 50:50%.

Variable	df	F Ratio	Prob	Post hoc
% crab landings commercial	3	29.97	<0.0001	90 > 80 = 70 = 50
% crab landings recreational	3	29.97	<0.0001	50 = 30 = 20 > 10
% diseased crabs	3	2.55	0.0916	90 = 50 = 80 = 70
% juvenile crabs	3	2.55	0.0918	90 = 80 = 70 = 50
% female crabs	3	0.75	0.5369	70 = 50 = 90 = 80

Table 3-4: Sensitivity analysis ANOVAs for five measures of model population structure versus three levels of river discharge flow deviation. Flow conditions were adjusted as follows: drought conditions (-30% of normal flow), normal flow conditions, and flooding conditions (+30% of normal flow) that modified a historical seasonal baseline derived from the 65-year historical record of Edisto River discharge (USGS station 02175000).

Variable	df	F Ratio	Prob	Post hoc
% crab landings commercial	2	16.27	0.0004	Low > Norm = High
% crab landings recreational	2	16.27	0.0004	High = Norm > Low
% diseased crabs	2	20.59	0.0001	Low > Norm = High
% juvenile crabs	2	5.66	0.0185	Low =>Norm =>High
% female crabs	2	0.30	0.7441	High = Norm = Low

Table 3-5.1: Sensitivity analysis ANOVAs for five measures of model population structure versus three levels of commercial fishing closed season regulations (None, Half, Full).

Variable	df	F Ratio	Prob	Post hoc
% crab landings commercial	2	6.65	0.0035	None = Half > Full
% crab landings recreational	2	6.65	0.0035	None = Half > Full
% diseased crabs	2	44.16	<0.0001	Full > Half > None
% juvenile crabs	2	7.90	0.0014	Full >=Half >=None
% female crabs	2	4.30	0.0210	Full >=Half >=None

Table 3-5.2: Sensitivity analysis ANOVAs for five measures of model population structure versus three levels of recreational fishing closed season regulations (None, Half, Full).

Variable	df	F Ratio	Prob	Post hoc
% crab landings commercial	2	15.16	<0.0001	None = Half > Full
% crab landings recreational	2	15.16	<0.0001	None = Half > Full
% diseased crabs	2	24.66	<0.0001	Full > Half > None
% juvenile crabs	2	7.27	0.0022	Full >=Half >=None
% female crabs	2	7.94	0.0014	Full > Half = None

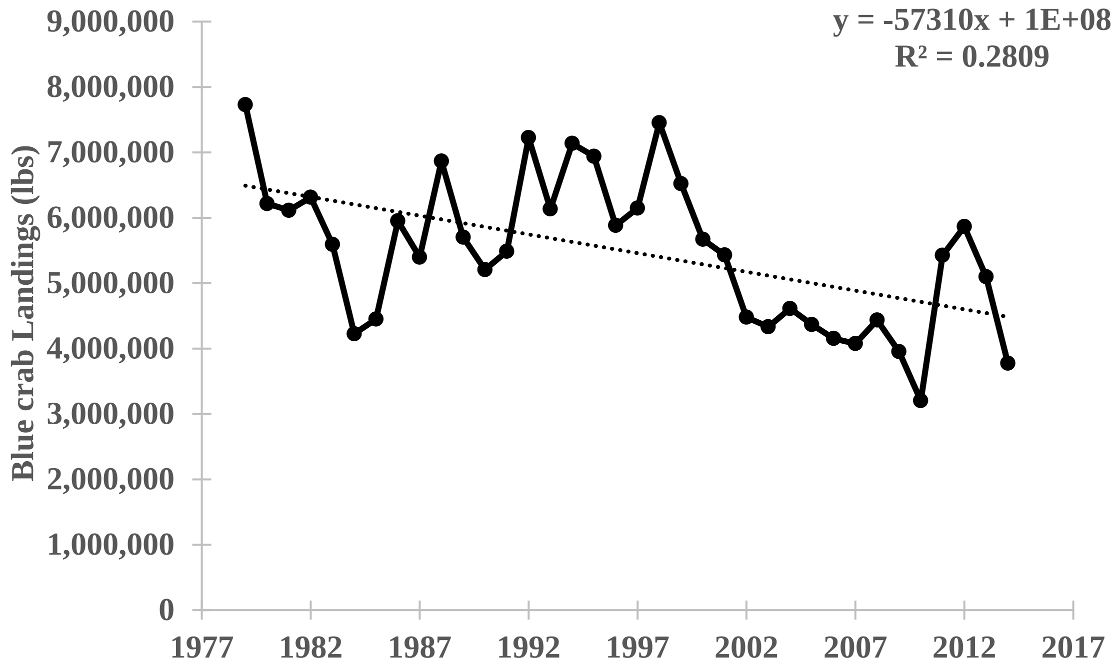

Figure 3-1. Reported annual blue crab commercial landings from 1966-2014 in South Carolina. The reported landings of the 2014 blue crab harvest were the second lowest (4 million pounds), behind 2010 landings (3 million pounds). The best-fit regression is shown by the dotted black line, showing an overall downward trend of landings. Data and graph provided by SCDNR, OFM (2015). Figure adapted from McClellan et al. (2015).

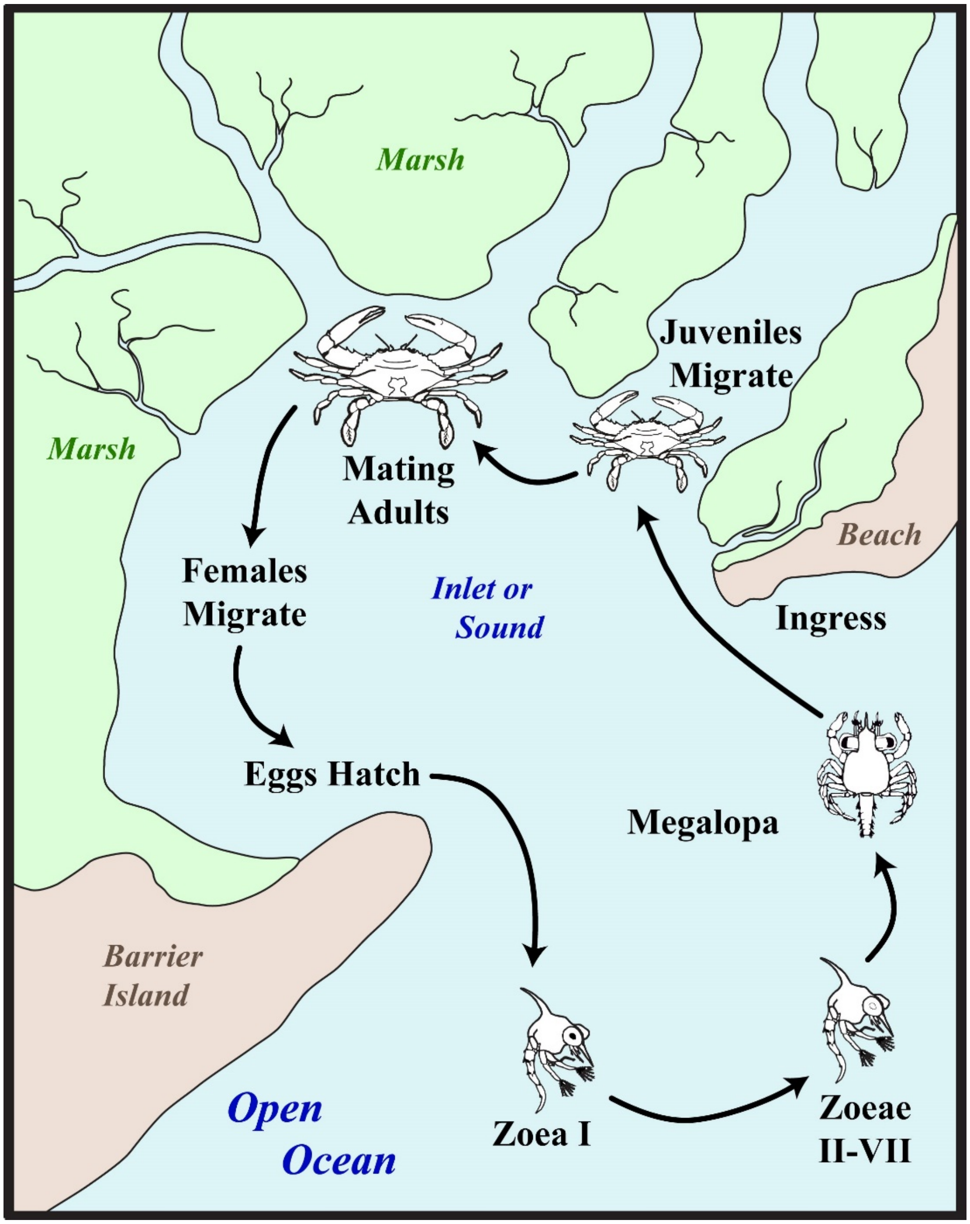

Figure 3-2. Simplified habitat utilization of the blue crab throughout various life stages. (Graphic provided by SCDNR, Marine Resources Division).

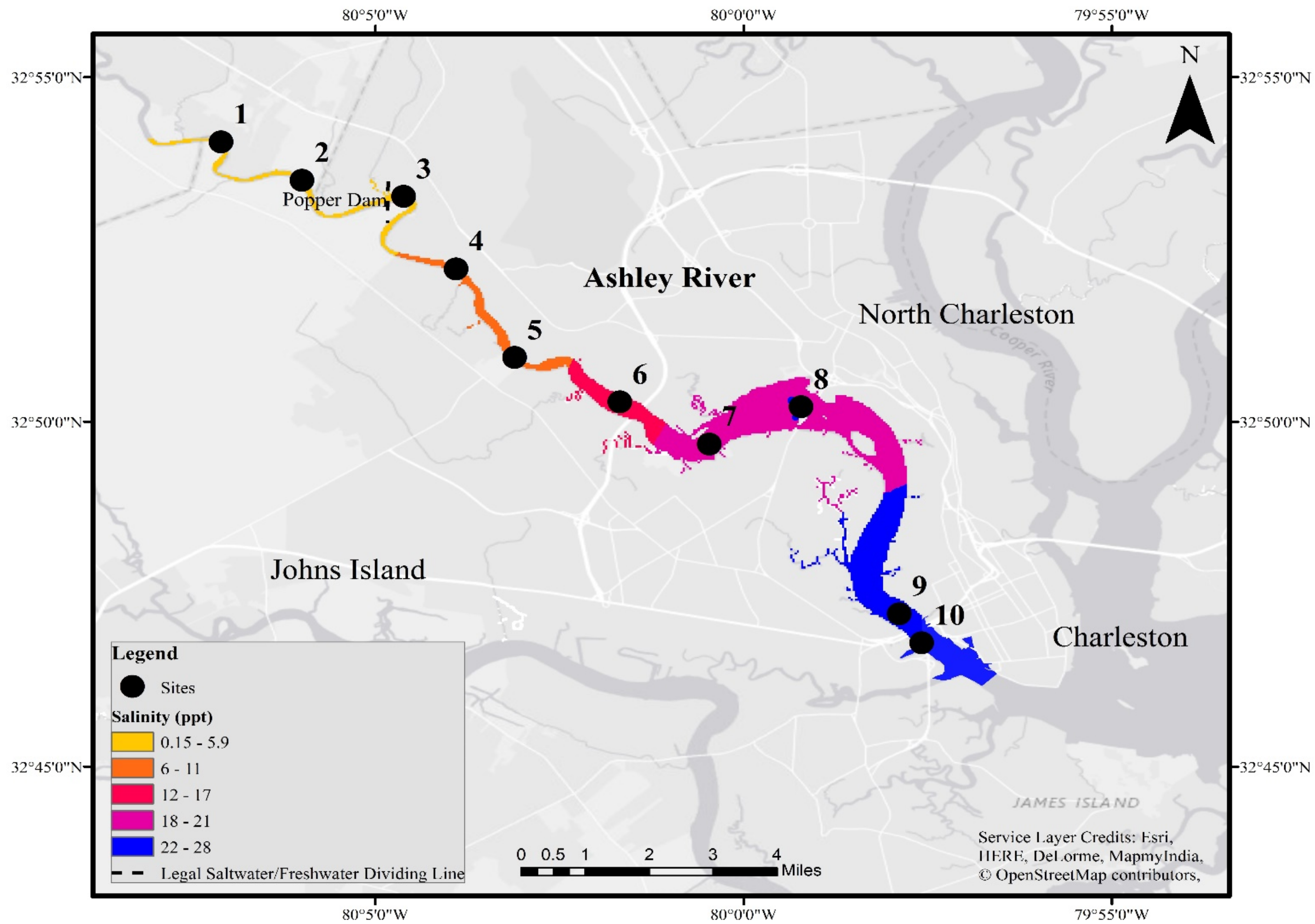

Figure 3-3. Map of fisheries independent study sites in the Ashley River, South Carolina. Site 1 is the furthest up river and represents the most freshwater site. Site 10 is the furthest river downstream and closest to the Charleston Harbor. Map created using ESRI ArcGIS 10.4.1. The salinity layer is an IDW built from the 13 averaged bottom salinities on the dates when the pots were set.

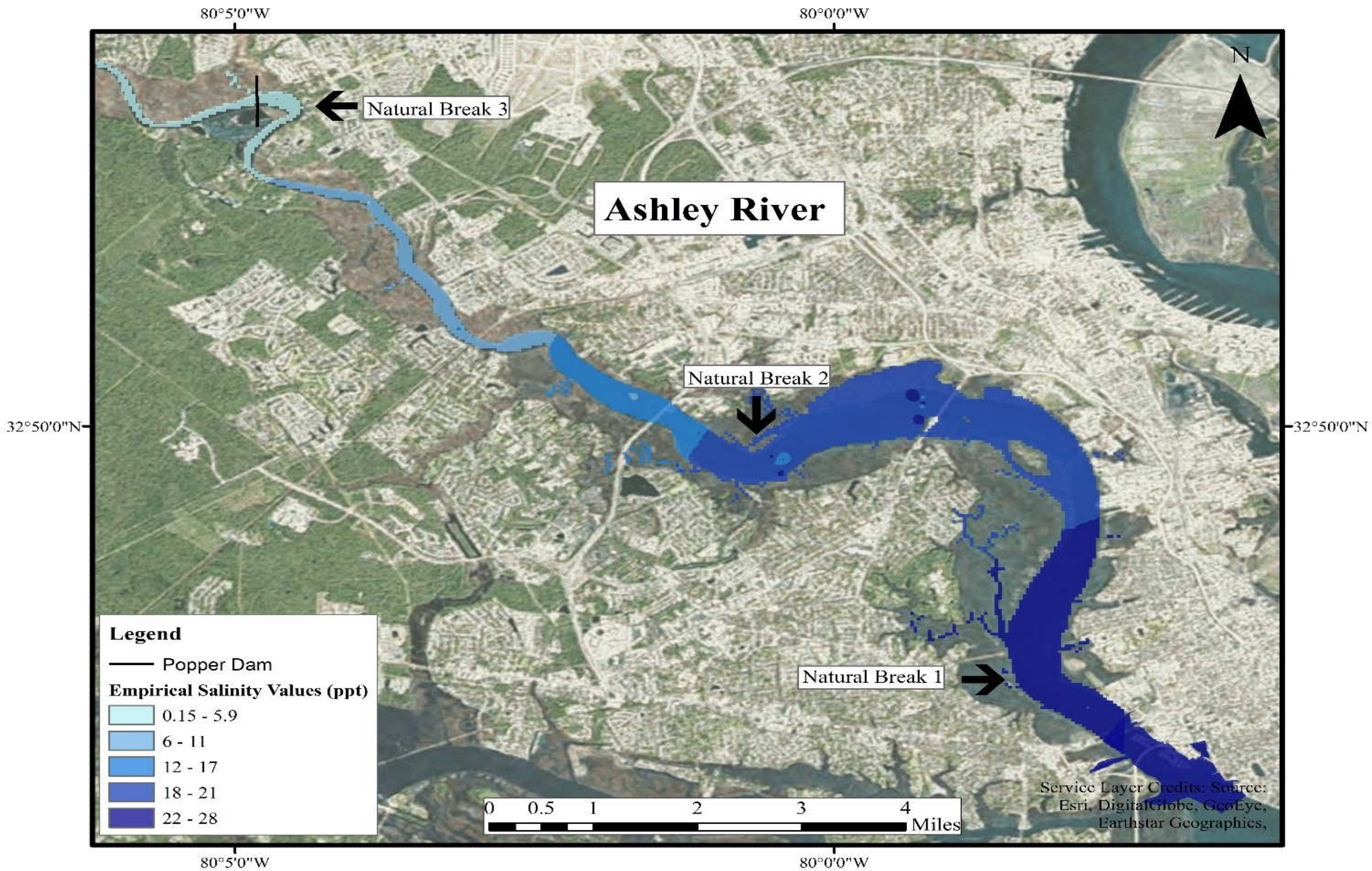

Figure 3-4.1. The Ashley River, South Carolina. The salinity profile of the river is displayed in the blue gradient, and the legal-freshwater-saltwater dividing line (Popper Dam) is shown. There are three distinctive breaks in the river, accompanied by an overall shift in the salinity gradient, with each differing geomorphological structure. Figure 3b (below) shows the SCBCRABS model reflecting the geomorphology of the river.

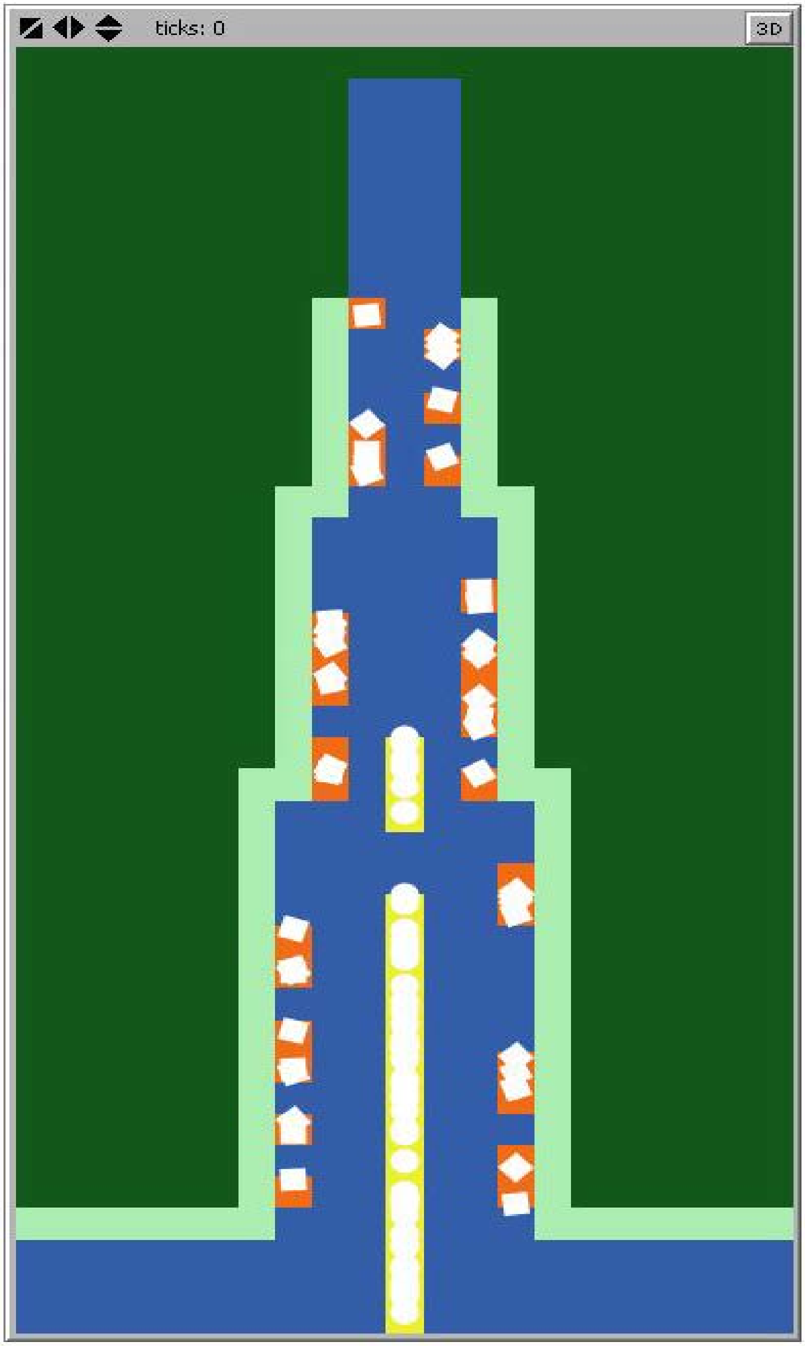

Figure 3-4.2. SCBCRABS-ASHLEY initial set-up routine, without any individuals populating the interface. Each patch color is representative of a geological feature found in the wetland area: dark green is upland, light green is wetland, dark blue is the water within the river system, orange patches are recreational crab traps, and yellow patches are commercial crab traps (SCBCRABS-ASHLEY, NetLogo 4.0.5).

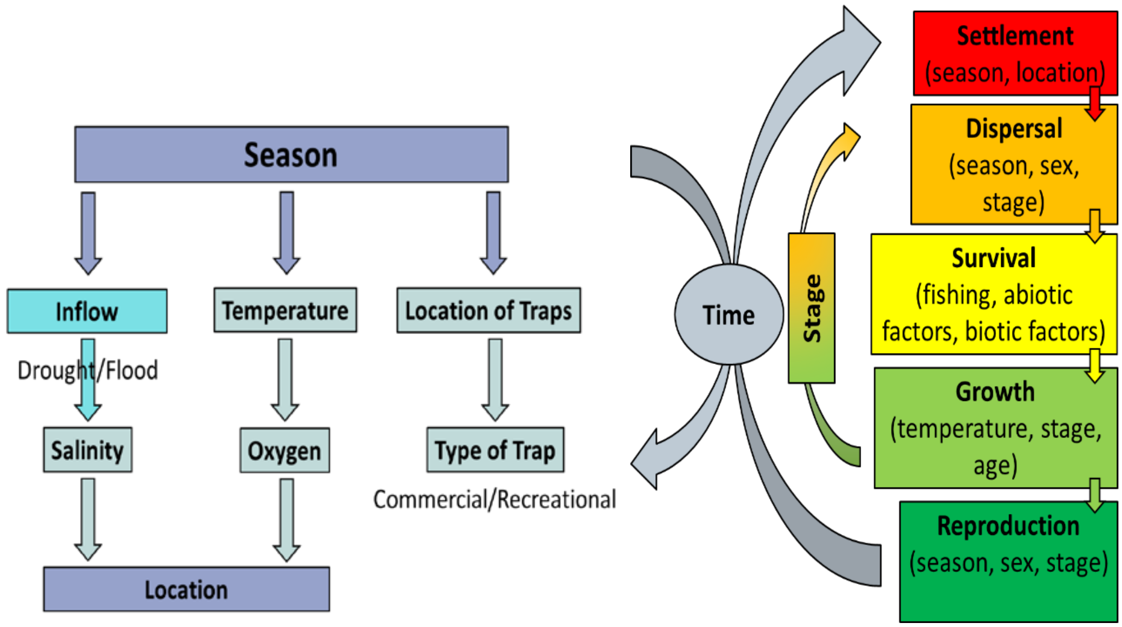

Figure 3-5. Individual Based Model subroutines, a relationship of biotic and abiotic variables and the blue crab life stage subroutines. Figure adapted from (Childress and Parmenter 2012).

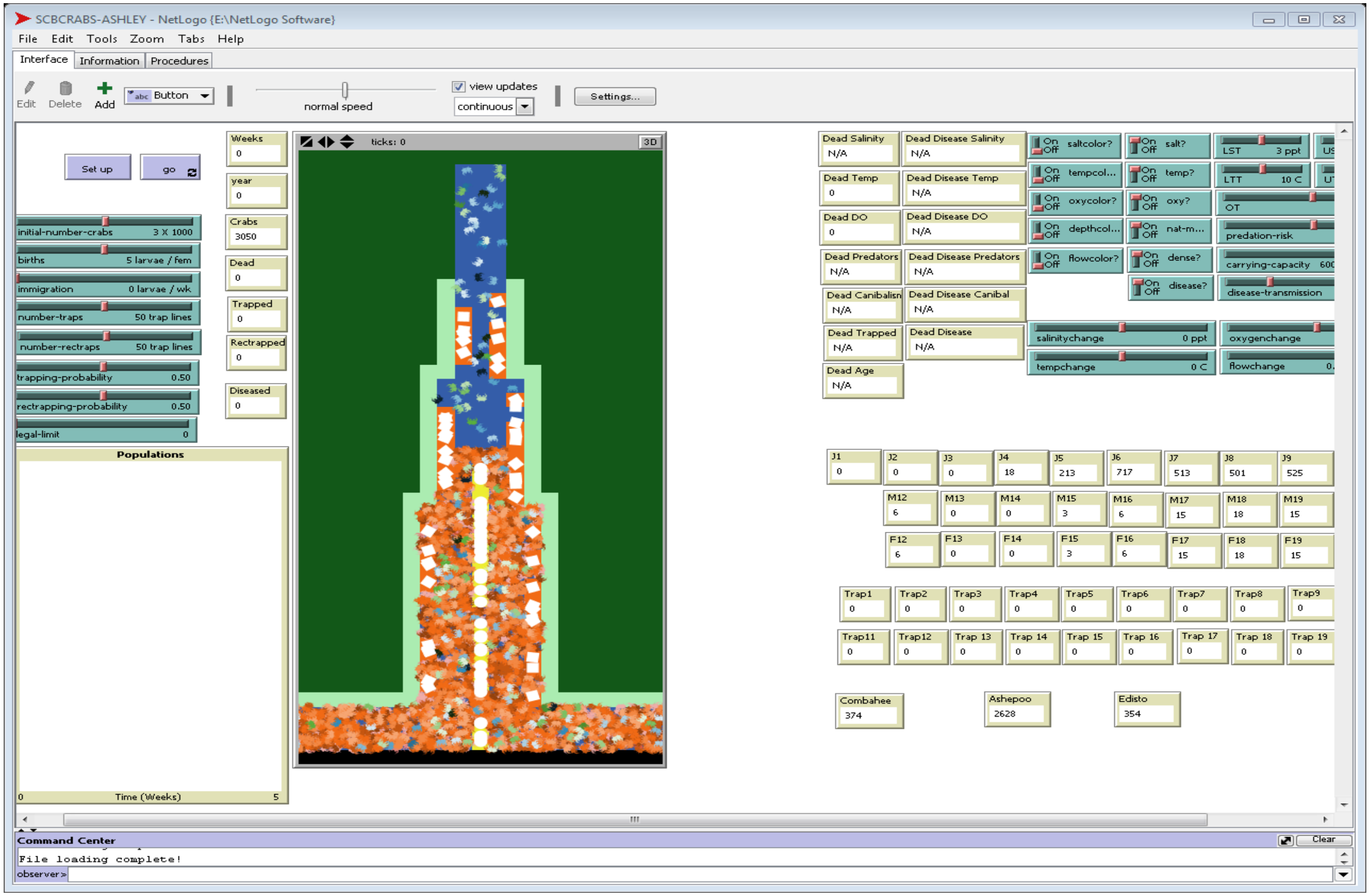

Figure 3-6. SCBCRABS-ASHLEY initial set-up routine, with agents populating the “click and point” interface. Each patch color is representative of a geological feature found in the wetland area: dark green is upland, light green is wetland, dark blue is the water within the river system, orange patches with white squares are recreational crab traps, and yellow patches with circles are commercial crab traps (SCBCRABS-ASHLEY NetLogo 4.0.5).

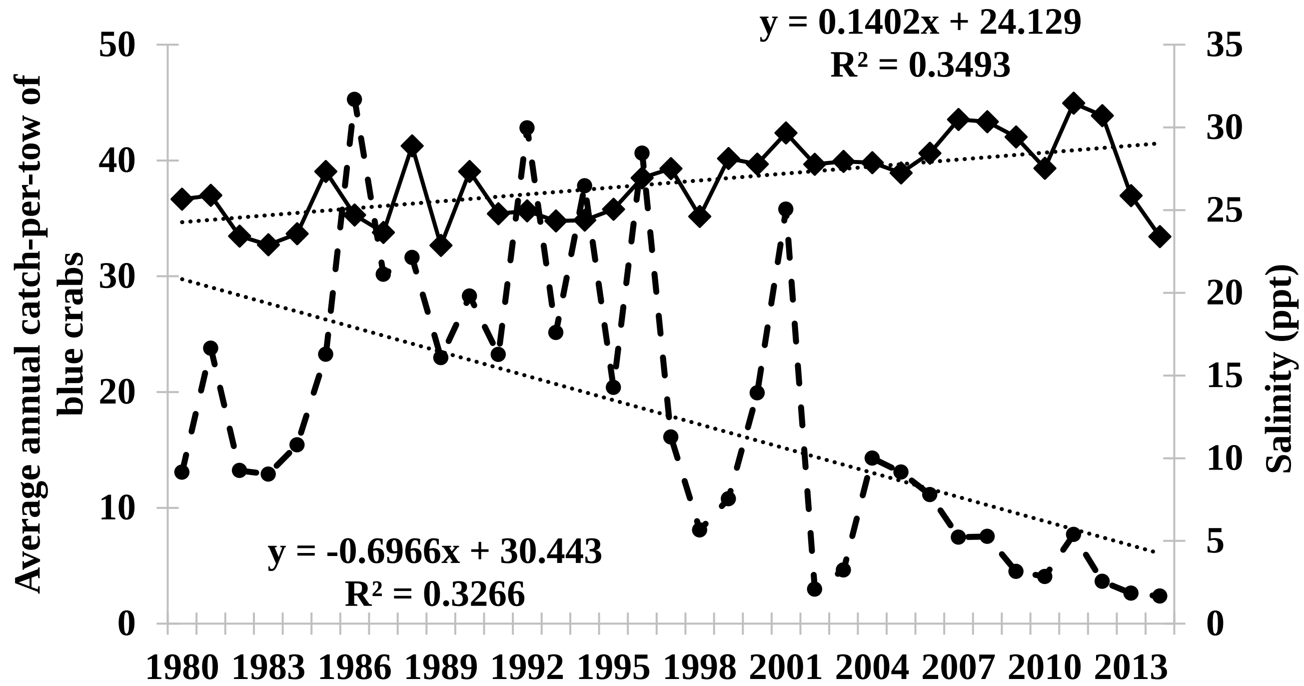

Figure 3-7. Crab catch per unit effort (CPUE) from SCDNR trawl data collected from 1980-2014 (dashed black line), and the salinity (ppt) recordings (solid black line). Recorded salinities are increasing over time while the crab catch has been decreasing. Data and graph compiled by David Whitaker (SCDNR).

Field Figures

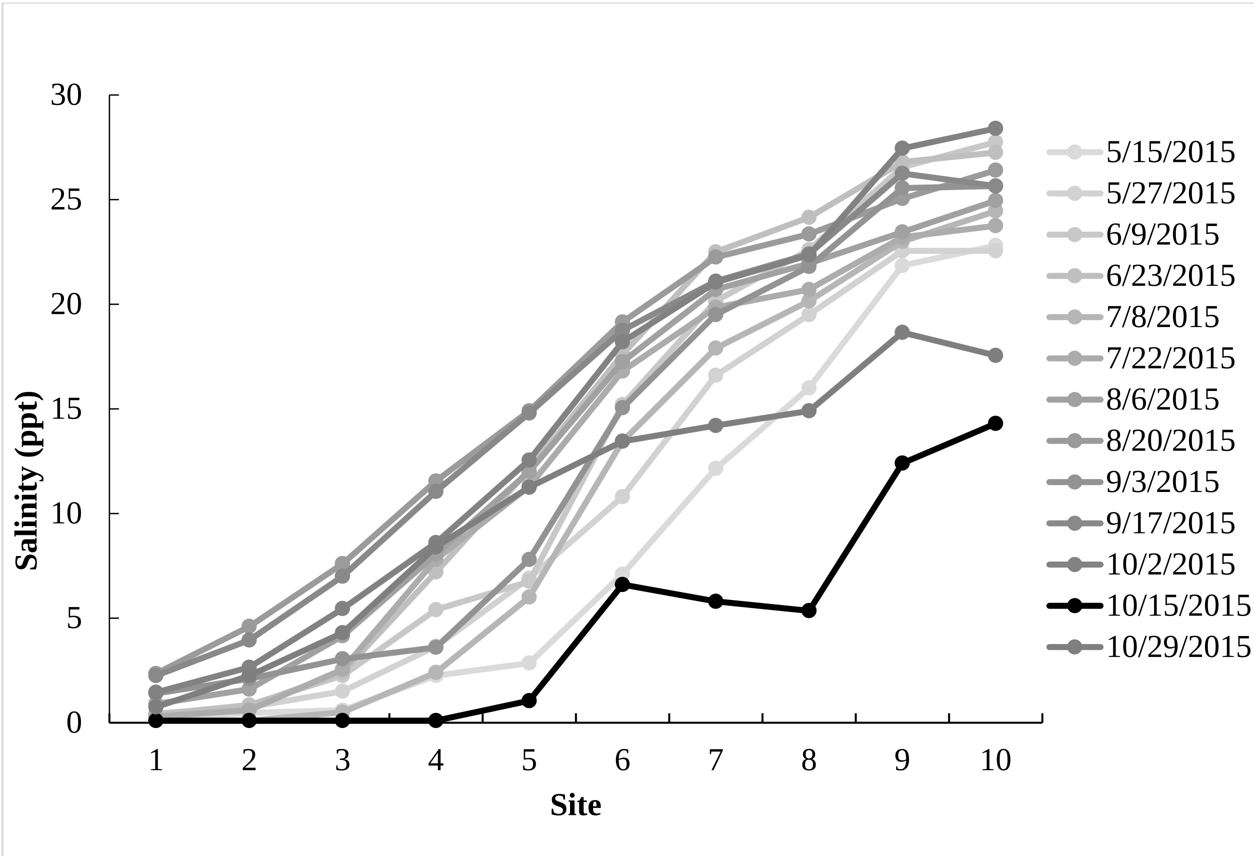

Figure 3-8. The temporal and spatial distribution of averaged bottom salinity from channel and shoreline pots across the 10 sites. Site 1 is the furthest up river and represents the most freshwater site.

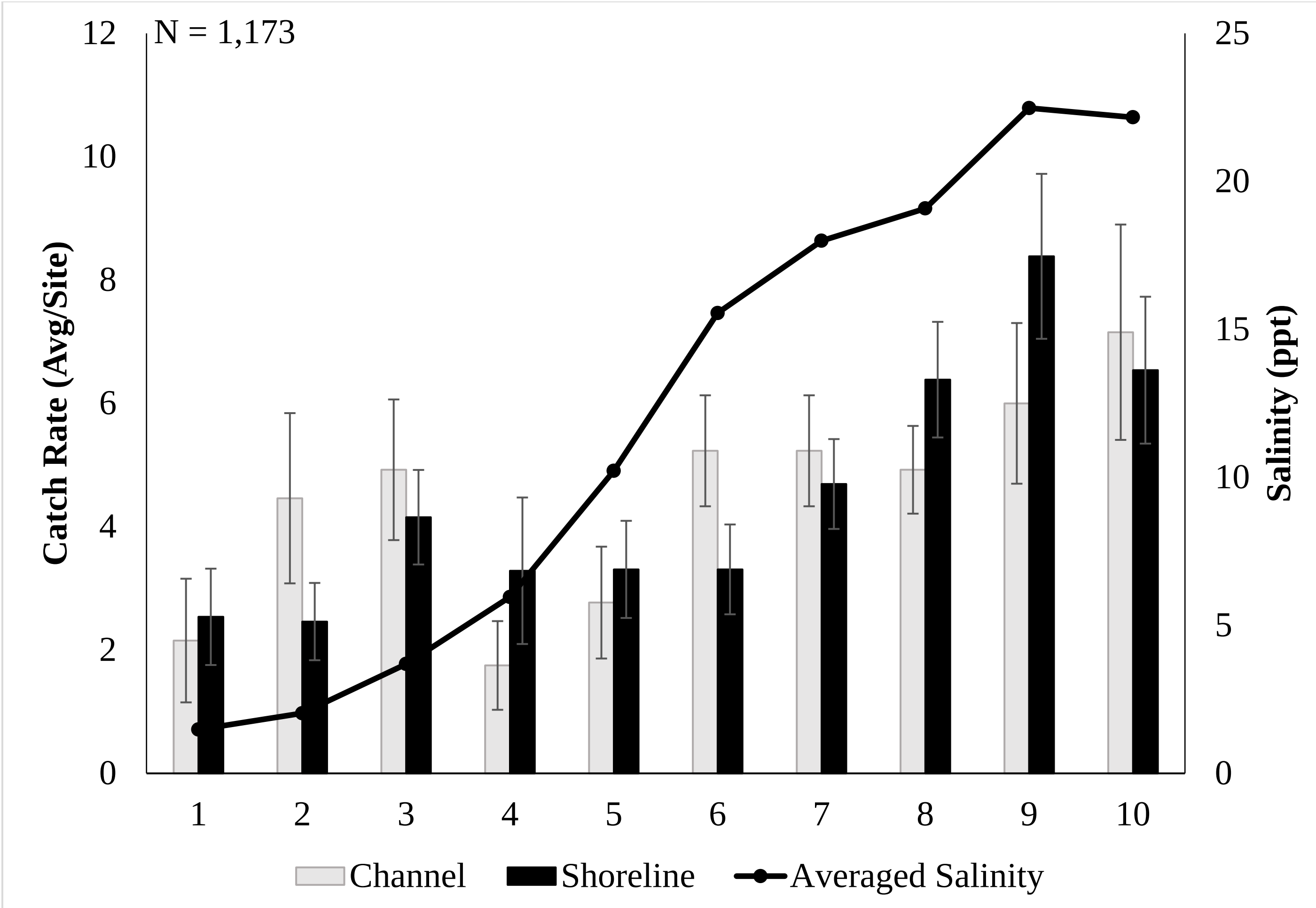

Figure 3-9. The average blue crab catch rate for both the channel and shoreline pots for the 10 sites across all sampling periods. The average salinity for each of those sites is also shown. Site 1 is the furthest up river and represents the most freshwater site. The salinity is displayed on the secondary vertical axis. The data callouts are the total crabs caught throughout the season in each pot.

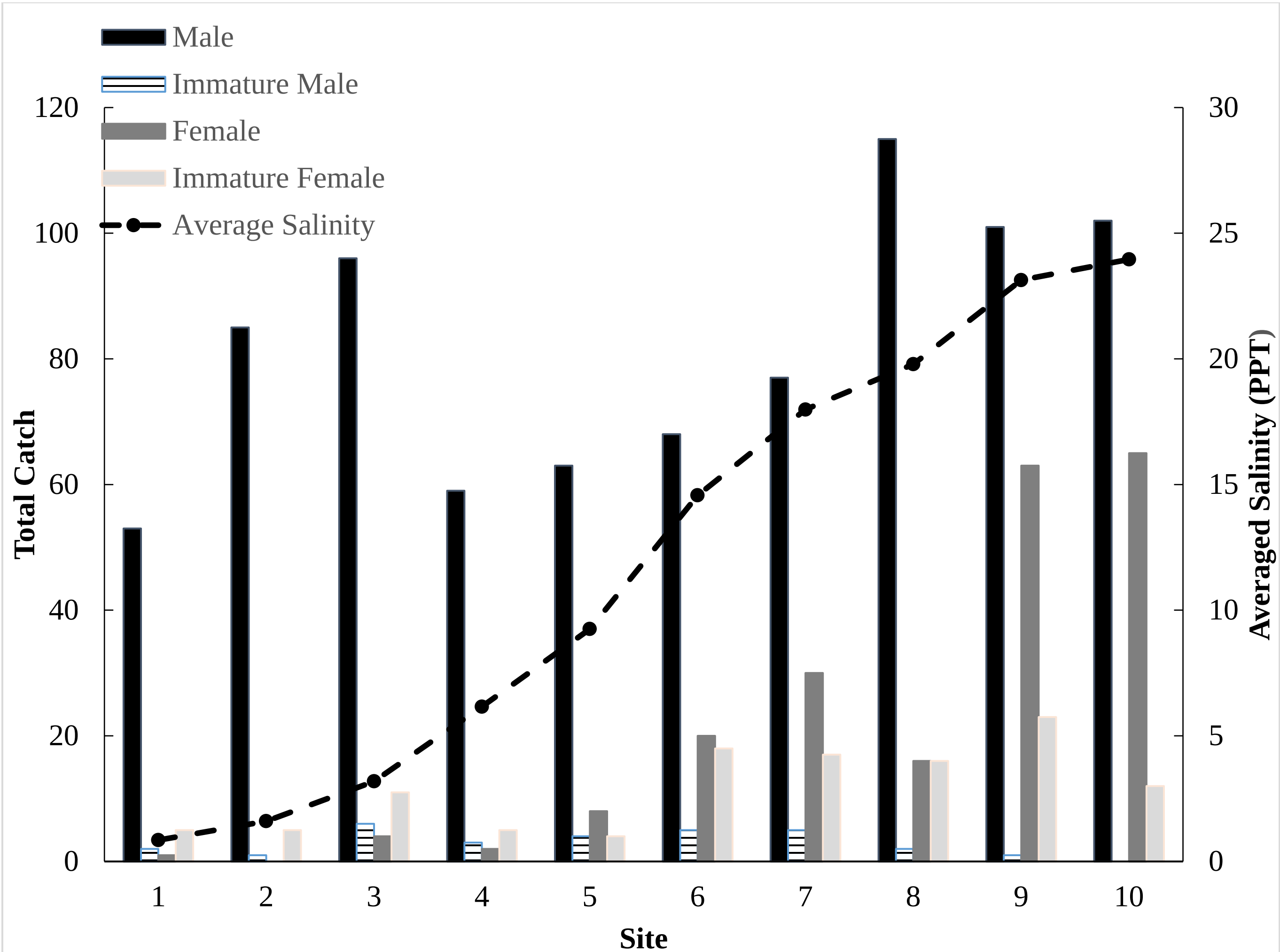

Figure 3-10. Combined total blue crab catch for both the channel and shoreline pots for the 10 sites across all sampling periods separated by blue crab sex and maturity status. The average salinity for each of those sites is also shown. Site 1 is the furthest up river and represents the most freshwater site.

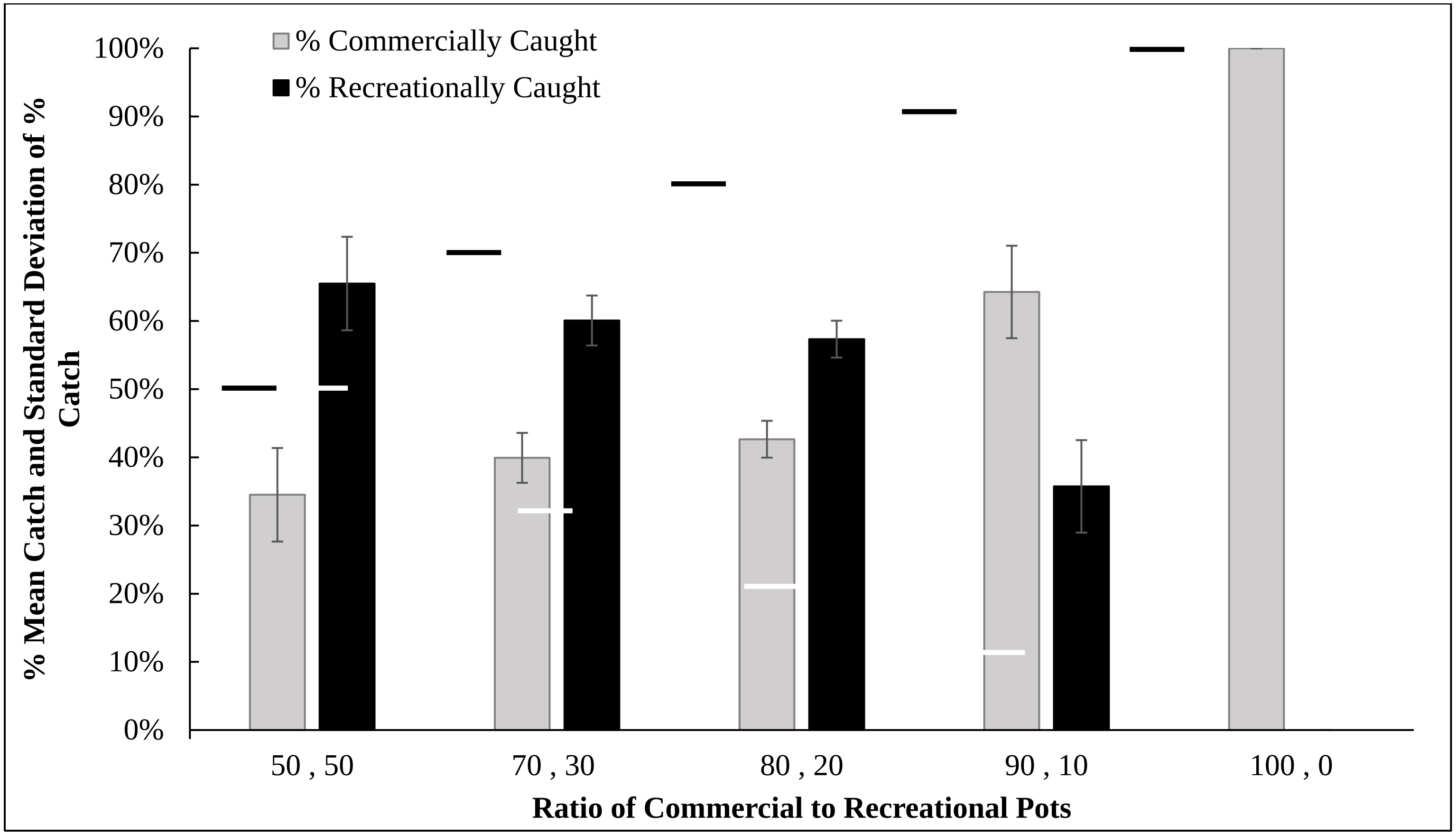

Figure 3-11. The percent mean catch of crabs with varying recreational and commercial fishing pressure. The percent mean catch for each fishery is represented on the vertical axis, and the standard deviation for the percent catch was calculated and is shown in the error bars, while the ratio of fishing pressure (number of pots actively fishing) is represented on the horizontal axis. The white / black reference lines indicate the expected catch if pots had equal catch probabilities.

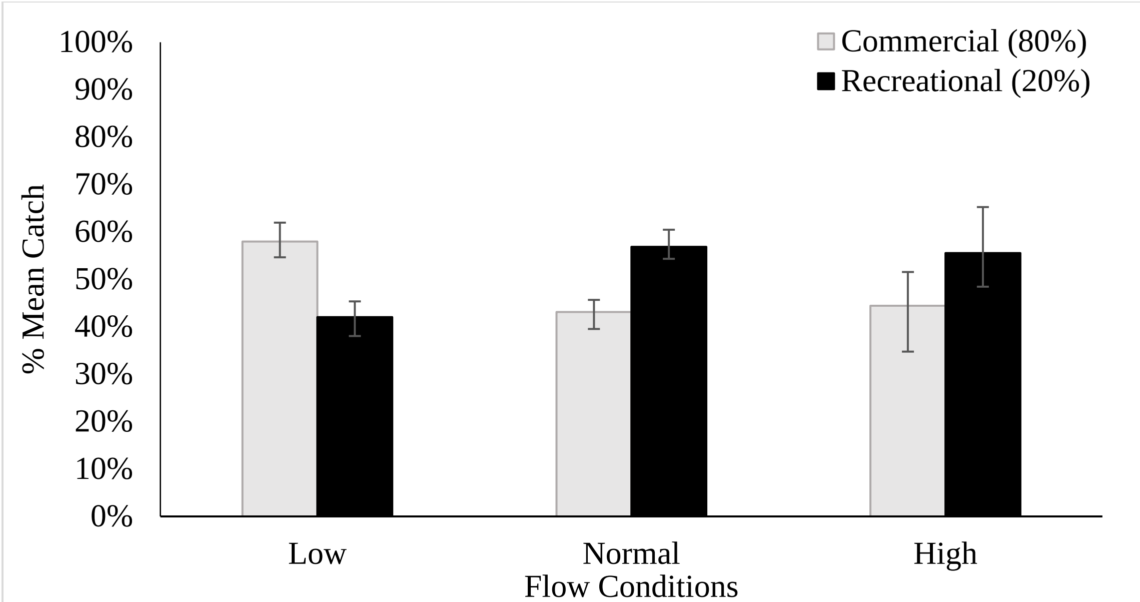

Figure 3-12. The rates of mean percent catch of commercial and recreational pots in the model at various flow conditions. Flow conditions were adjusted in the SCBCRABS-ASHLEY Model as follows: drought conditions (-30% of normal flow), normal flow conditions, and flooding conditions (+30% of normal flow) that modified a historical seasonal baseline derived from the 65-year historical record of Edisto River discharge (USGS station 02175000). The catch rates are based on a historical ratio of 80 commercials to 20 recreational pots. There were no fishing restrictions. The error bars are the calculated standard error of the mean.

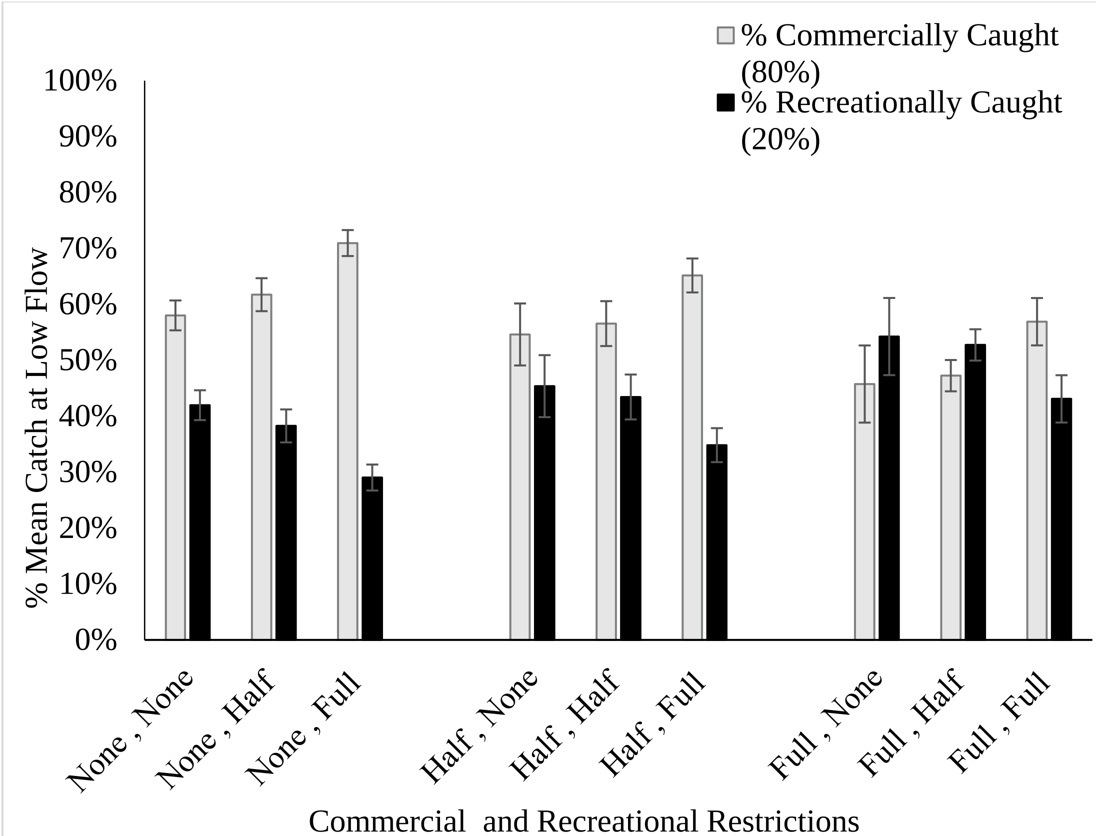

Figure 3-13. The influence of seasonal restrictions on commercial and recreational catch at low flow, at the 80:20 commercial to recreational ratio. On the horizontal axis, varying fishery closures are represented: no seasonal restrictions are labeled as "None", crabbing restrictions during April-May are labeled as "Half", and a full seasonal closure from April-late September is labeled as "Full". The error bars are the calculated standard error of the mean.

4. SUMMARY AND CONCLUSION

The fisheries-dependent survey of recreational license holders throughout South Carolina revealed some interesting trends in recreational fishing for blue crab, some of which were in contrast to what had been observed in 1997 (Low 1998). While both the current and historical surveys showed higher blue crab fishing from residents of coastal counties, this was to be expected. However, there is an overall decrease in the numbers of recreational license holders reporting crabbing activity between 1998 and 2015. However, it is interesting to note that while Low (1998) received more postcards back from the mail-out overall, there were lower numbers of respondents that recorded blue crabbing events as compared to 2015. This suggests that the 2015 survey may have been biased towards being returned by recreational fishermen that fished for blue crabs. While crab pots were the most preferred fishing method for both the 1997 and 2015 surveys in both the summer and fall seasons, there was a transition from the usage of baited strings towards using drop nets. This transition of gear type preference could be explained by the accessibility and ease of one gear type over another, as drop nets are more commercially available.

While date and site impacted, blue crab catch in the Ashley River, there was no significant difference in blue crab catch rates between commercial and recreational pots. This may be due to the fact that there were no significant differences in bottom salinity between the commercial and recreational pots at the same site. The relationship between salinity and blue crab habitat usage by sex and life stage is well documented (e.g., Tagatz

1971, Childress 2010, Parmenter 2012). Adult males are more commonly found in lower salinity water, while adult females migrate seaward and will be more abundant in intermediate and higher salinities, as spawning typically takes place in high oceanic salinities (Tagatz 1971). We also observed this in the field survey, with the majority of adult females found at the highest salinity sites throughout the season. However, there was no significant relationship between blue crab catch and salinity values, suggesting that other environmental variables may also be influencing blue crab habitat selection.

During drought events, the lack of freshwater inflow can result in increased salinity in estuarine river systems (Childress 2010). In this case, blue crabs respond both behaviorally, by following the salt wedge up the tidal river, and physiologically, by performing osmoregulation in varying salinities (Ward 2012). Long-term fisheries independent surveys along the South Carolina coast, conducted by the SCDNR have shown an overall increase in salinities from 1980 to 2012 with a concurrent decrease in blue crab catch. This correlation suggests that reduced rainfall and river flow rates may be related to declining crab population abundance. This could potentially be explained by several mechanisms, including decreased optimal nursery habitat, negative physiological responses to higher salinity, increased disease prevalence (*Hematodinium* sp.), and declining numbers of spawners due to differential catch rates of males and females. Continued monitoring of blue crabs in the Ashley River along this salinity gradient would be helpful in interpreting how and why blue crab abundances shift.

Due to the projected changes in weather patterns and estuarine salinity as a function of a changing climate, this project was the first step in designing and performing a field survey of how blue crabs may change habitat preferences. The field study complemented current SCDNR crab potting by providing more information about blue crab size frequencies and abundances above the freshwater/saltwater dividing line. Because of the success of this project, SCDNR adopted the field study along the salinity gradient as part of regular field sampling. Including more stations along a salinity gradient from freshwater to full saline will give managers a better insight to what is happening to the population and relate that to environmental conditions.

Overall, this study provided updated information as to the impact and effort of recreational fishing. As we created an online survey for recreational blue crabbers, the SCDNR could potentially use that platform to survey recreational fishermen for several years in a row. This could be especially useful years that receive extreme weather events that may be tied to climate change (i.e. hurricane conditions, drought, increased rainfall, etc.) or economic fluctuations. It would also be useful to compare seasonal and annual changes in recreational fishing pressure to reveal temporal patterns along the coast.

References

2016-2017 Saltwater Fishing Regulations. (2016). South Carolina Department of Natural Resources. Retrieved from http://www.dnr.sc.gov/regs/saltwaterregs.html.

Aguilar, R., Johnson, E. G., Hines, A. H., Kramer, M. a., and Goodison, M. R. (2008). Importance of Blue Crab Life History for Stock Enhancement and Spatial Management of the Fishery in Chesapeake Bay. *Reviews in Fisheries Science, 16*(1–3), 117–124. https://doi.org/10.1080/10641260701681599

Alber, M. (2002). A Conceptual Model of Estuaries Freshwater Inflow Management. *Estuaries*, *25*(6), 1246–1261.

Altieri, A. H., Bertness, M. D., Coverdale, T. C., Herrmann, N. C., and Angelini, C. (2012). A trophic cascade triggers collapse of a salt-marsh ecosystem with intensive recreational fishing. *Ecology*, *93*(6), 1402-1410.

Allen, J., and Lu, K. (2003). Modeling and prediction of future urban growth in the Charleston region of South Carolina: a GIS-based integrated approach. Ecology and Society, 8(2), 2.

Archambault, J. A., Wenner, E. L., and Whitaker, J. D. (1990). Life history and abundance of blue crab, *Callinectes sapidus* Rathbun, at Charleston Harbor, South Carolina. *Bulletin of Marine Science*, 46, 145-158.

Bell, M. C., Addison, J. T., and Bannister, R. C. A. (2001). Estimating trapping areas from trap-catch data for lobsters and crabs. *Marine and Freshwater Research*, *52*(8), 1233. https://doi.org/10.1071/MF01175

Blue Crab Update (2004). State of South Carolina's Coastal Resources. South Carolina Department of Natural Resources. http://www.dnr.sc.gov/marine/mrri/pubs/yr2004/statebluecrab. Accessed February 18, 2016.

Blue Crab Update (2007). State of South Carolina's Coastal Resources. South Carolina Department of Natural Resources. http://www.dnr.sc.gov/marine/mrri/pubs/yr2007/crabs07.pdf. Accessed February 18, 2016.

Bunnell, D. B., and Miller, T. J. (2005). An individual-based modeling approach to spawning-potential per-recruit models : an application to blue crab (*Callinectes sapidus*) in Chesapeake Bay. *Canadian Journal of Fisheries and Aquatic Science, 2572*, 2560–2572. https://doi.org/10.1139/F05-153.

Chesapeake Bay Stock Assessment Committee. (2005). Chesapeake Bay blue crab advisory report. Available from NOAA Chesapeake Bay Office, Annapolis, MD.

Retrieved from http://chesapeakebay.noaa.gov/images/stories/fisheries/keyFishSpecies/2016cbsacbluecrabadvisoryreport.pdf.

Childress, M.J. (2007). SCBCRABS: South Carolina Blue Crab Region Abundance Biotic Simulation: a user manual. SC Sea Grant Consortium (May 2007).

Childress, M. J. (2010). Modeling the impact of drought on South Carolina blue crabs using a spatially-explicit individual-based population model. Abstract from the Proceedings of the 2010 South Carolina Water Resources Conference, Columbia, SC.

Childress, M. J., Parmenter, K. J., Childress, M. J., and Parmenter, K. J. (2012). Dying of Thirst: Impact of Reduced Freshwater Inflow on South Carolina Blue Crabs. The Proceedings of the 2010 South Carolina Water Resources Conference, Columbia, SC.

Coleman, F. C., Figueira, W. F., Ueland, J. S., Crowder, L. B. (2004). The impact of United States recreational fisheries on marine fish populations. Science 305:1958–1960.

Colton, A.R., Wilberg, M.J., Coles, V.J. and Miller, T.J. (2014), An evaluation of the synchronization in the dynamics of blue crab *(Callinectes sapidus)* populations in the western Atlantic. Fish. Oceanogr., 23: 132–146. doi:10.1111/fog.12048.

Conrad, P., and Darby, L. (2016). Development of a Coastal Drought Index Using Salinity Data. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-15-00171.1, in press.

Cooke, S. J., and Cowx, I. G. (2004). The role of recreational fishing in global fish crises. *BioScience*, *54*(9), 857-859.

Darnell, R. M. (1959). Studies of the life history of the blue crab (*Callinectes sapidus* Rathbun) in Louisiana waters. *Transactions of the American Fisheries Society*, 88(4), 294-304.

Fedler, A. J., and Ditton, R. B. (2001). Dropping out and dropping in: a study of factors for changing recreational fishing participation. North American Journal of Fisheries Management, 21(2), 283-292.

Fowler AE, DeLancey LB. (2015). State of the resource update: Blue Crabs. Marine Resources Division, South Carolina Department of Natural Resources. http://www.dnr.sc.gov/marine/species/bluecrab.html. Accessed 9 Mar 2016.

Grimm, V., and Railsback, S. F. (2005). Individual-based modeling and ecology (Vol. 2005). Princeton: Princeton university press.

Jones, K. (2009). South Australian recreational fishing survey 2007/08. Fisheries Division, Primary Industries and Resources South Australia, December. http://www.ffc.org.au/FFC_files/SA%20rec%20fishing%20survey/A618891_South_Australian_Recreational_Fishing_Survey_2007-08__3_.pdf

Knapp, A. K., Beier, C., Briske, D. D., Classen, A. T., Luo, Y., Reichstein, M., … Weng, E. (2008). Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems. *BioScience*, *58*(9), 811. https://doi.org/10.1641/B580908

Lee, R. F., and Frischer, M. E. (2004). The decline of the blue crab. American Scientist, 92, 548–553.

Lipcius, R. N., and Stockhausen, W. T. (2002). Concurrent decline of the spawning stock, recruitment, larval abundance, and size of the blue crab Callinectes sapidus in Chesapeake Bay. *Marine Ecology Progress Series*, *226*, 45-61.

Low, R. A. (1998). Survey of recreational blue crabbing by marine recreational fisheries stampholders. Technical Data Report 30. South Carolina Department of Natural Resources, Marine Resources Division, Office of Fisheries Management.

Lowry, R. (2016). VassarStats [Computer Software]. Poughkeepsie, N.Y. Vassar College. Retrieved from http://vassarstats.net/abc.html.

McClellan K, Davis J, Childress M, Fowler AE. (2015). Assessing the South Carolina blue crab fishery in the face of climate variability and change: A state of the knowledge report. In review. South Carolina Sea Grant Consortium. 63pp.

McDonald, J.H. 2014. Handbook of Biological Statistics (3rd ed.). Sparky House Publishing, Baltimore, Maryland.

Mense, D. J., Wenner, E. L. (1989). Distribution and abundance of early life history stages of the blue crab, *Callinectus sapidus*, in tidal marsh creeks near Charleston, South Carolina. *Estuarie*s, 12, 157-168.

Miller, T. J., Fogarty, M. J., Lipcius, R., and Hoenig, J. (2000). Design of a Recreational Fishing Survey and Mark-Recapture Study for the Blue Crab, Callinectes sapidus, in Chesapeake Bay.

Milliken, M. R., and Williams, A. B. (1984). Synopsis of biological data on the blue crab, Callinectes sapidus Rathbun. National Oceanic and Atmospheric Administration Technical Report. National Marine Fisheries Service 1, Food and Agriculture Organization of the United Nations Fish Synopsis, 138: 1-39.

Muffley, B., Lurig, L., Mahnke, G. N., and Driscoll, H. (2007). Survey of New Jersey's Blue Crab, Callinectes sapidus, Recreational Fishery, Year 1-Delaware Bay.

Parmenter KJ. (2012). The effects of drought on the abundance of the blue crab, *Callinectes sapidus*, in the ACE Basin NERR in South Carolina. PhD Dissertation. Biological Sciences. Clemson University. pp 1-189.

Pflugh, K. K., Stern, A. H., Nesposudny, L., Lurig, L., Ruppel, B., and Buchanan, G. A. (2011). Consumption patterns and risk assessment of crab consumers from the Newark Bay Complex, New Jersey, USA. Science of the Total Environment, 409(21), 4536-4544.

R Development Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from https://www.R-project.org/.

Sharov, A. F., Vølstad, J. H., Davis, G. R., Davis, B. K., Lipcius, R. N., and Montane, M. M. (2003). Abundance and exploitation rate of the blue crab (*Callinectes sapidus*) in Chesapeake Bay. Bulletin of Marine Science, *72*(2), 543-565.

Smith, M. T., Addison, J. T. (2003). Methods for stock assessment of crustacean fisheries. *Fisheries Research*, *65*(1–3), 231–256. https://doi.org/10.1016/j.fishres.2003.09.017

Stagg, C., and Whilden, M. (1997). The history of Chesapeake Bay's blue crab (*Callinectes sapidus*): fisheries and management. Investigaciones Marinas, *25*(January 1997), 93–104. https://doi.org/10.4067/S0717-71781997002500007

Steele, P. and T.M. Bert. (1998). The Florida blue crab fishery: history, status, and management. Journal of Shellfish Research 17:441-449.

Sturdivant, S. K., and Clark, K. L. (2011). An evaluation of the effects of blue crab (Callinectes sapidus) behavior on the efficacy of crab pots as a tool for estimating population abundance. *Fishery Bulletin*, *109*(1), 48-55.

Sutinen, J., Johnston R.J. (2003). Angling management organizations: integrating the recreational sector into fishery management. Marine Policy. 27(6), 471-487.

Tagatz ME. (1971). Osmoregulatory ability of blue crabs in different temperature-salinity combinations. *Chesapeake Science*, 12 (1), 14-17.

U.S. Census Bureau. (2015). SOUTH CAROLINA - 2010 Census Results Percent Change in Population by County: 2000 to 2010. Retrieved from https://www.census.gov/geo/maps-data/maps/thematic.html

Van Den Avyle MJ, Fowler DL. (1984). Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic) – blue crab. U.S. Fish and Wildlife Service FWS/OBS-82/11.19. U.S. Army Corps of Engineers, TR EL-82-4. 16 pp.

Venables, W. N. and Ripley, B. D. (2002) Modern Applied Statistics with S. Fourth Edition. Springer, New York. ISBN 0-387-95457-0.

Voss, C. M., Browder, J. A., Wood, A., and Michaelis, A. (2015). Factors driving the density of derelict crab pots and their associated bycatch in North Carolina waters. *Fishery Bulletin*, 113(4), 378–391. Retrieved *Academic OneFile*, Accessed 13 Mar. 2017.

Ward GH. (2012). The Blue Crab: A Survey with Application to San Antonio Bay. Center for Research in Water Resources. 210 pg.

Waltz, W. (1996). South Carolina saltwater fishing stamp survey, 1994, SCMRD, OFM, Charleston, SC.

Xiao, Y. (2000). A general theory of fish stock assessment models. Ecological Modelling, 128(2–3), 165–180. https://doi.org/10.1016/S0304-3800(00)00199-X.

APPENDIX A

Postcards distributed for the Summer cohort and the Fall cohort.

DNR
www.dnr.sc.gov

1. What **County** do you live in? ______________________

2. Have you participated in a SCDNR recreational crabbing survey in the past year?
YES NO *(please circle)*

3. Did you go crabbing this year (2015)?
YES NO *(please circle)*

4. How many **Total Trips** did you make crabbing using your permit? _________

5. How many crabbing **Trips** did you conduct in each month?

_______ JULY _______ AUGUST

6. Please indicate the number of **Trips** you made in each **Area**. (*Refer to map on cover letter*)

_______ Beaufort _______ Charleston _______ St. Helena Sd.

_______ Bulls Bay _______ Wadmalaw/Edisto Is. _______ Georgetown

7. Did you crab mostly from:

_______boat _______ dock _______bridge _______bank _______beach _______ pay-to-fish fishing pier

8. How many **Different People** assisted you on your crabbing trips? _______

9. What was your **Average Catch Per Trip** of blue crabs? _______

10. Which gears did you use?
_______ pot _______ baited string _______ drop net _______Other (*if other, please specify)*:

DNR
www.dnr.sc.gov

1. What **County** do you live in? ______________________

2. Have you participated in a SCDNR recreational crabbing survey in the past year?
YES NO *(please circle)*

3. Did you go crabbing this year (2015)?
YES NO *(please circle)*

4. How many **Total Trips** did you make crabbing using your permit? _________

5. How many crabbing **Trips** did you conduct in each month?

_______ SEPTEMBER _______OCTOBER

6. Please indicate the number of **Trips** you made in each **Area**. (*Refer to map on cover letter*)

_______ Beaufort _______ Charleston _______ St. Helena Sd.

_______ Bulls Bay _______ Wadmalaw/Edisto Is. _______ Georgetown

7. Did you crab mostly from:

_______boat _______ dock _______bridge _______bank _______beach _______ pay-to-fish fishing pier

8. How many **Different People** assisted you on your crabbing trips? _______

9. What was your **Average Catch Per Trip** of blue crabs? _______

10. Which gears did you use?
_______ pot _______ baited string _______ drop net _______ Other (*if other, please specify)*:

APPENDIX B

This appendix displays the NETLOGO code for SCBCRABS-ASHLEY 2.0. Code for the original model (SCBCRABS) was developed by Dr. Michael Childress and Brian Weeks. Code was appended by Dr. Michael Childress and Kelsey McClellan for this study.

SCBCRAB MODEL - Michael Childress and Brian Weeks

```
Globals
[ year week nat repro dead-turtles dead-turtles-sal dead-turtles-temp dead-turtles-oxy
dead-turtles-pred dead-turtles-dense dead-turtles-disease dead-turtles-disease-sal dead-
turtles-disease-temp dead-turtles-disease-oxy dead-turtles-disease-pred dead-turtles-
disease-dense dead-turtles-trap dead-turtles-trap-disease patch-data depth-data
randomnumberlist summermove wintermove spfallmove mouse-clicked mouse-double-
click clicked-turtle saltprob tempprob oxyprob denseprob hematoprob mortprob
diseaseprob ]

patches-own [ depth salinity oxygen temperature potnumber flow ]

breed [ J1 ]

breed [ J2 ]
breed [ J3 ]
breed [ J4 ]
breed [ J5 ]
breed [ J6 ]
breed [ J7 ]
breed [ J8 ]
breed [ J9 ]
breed [ J10 ]
breed [ J11 ]
breed [ M12 ]
breed [ M13 ]
breed [ M14 ]
breed [ M15 ]
breed [ M16 ]
breed [ M17 ]
breed [ M18 ]
breed [ M19 ]
breed [ M20 ]
breed [ F12 ]
breed [ F13 ]
breed [ F14 ]
breed [ F15 ]
breed [ F16 ]
breed [ F17 ]
breed [ F18 ]
breed [ F19 ]
breed [ F20 ]
```

```
breed [ traps ]
breed [ T1 ]
breed [ rectraps ]
breed [ RT1 ]

turtles-own [  natural-mortality reproduction lowersalinity-tolerance uppersalinity-
        tolerance hemato?
lowertemperature-tolerance uppertemperature-tolerance oxygen-tolerance age message?
        other-turtle stage ]
J11-own [ transition11 ] M12-own [ intrapM12 ] M13-own [ intrapM13  ] M14-own [
        intrapM14  ] M15-own [ intrapM15  ]
M16-own [ intrapM16  ] M17-own [ intrapM17 ] M18-own [ intrapM18 ] M19-own [
        intrapM19  ] M20-own [ intrapM20  ]
 F12-own  [ intrapF12  ] F13-own [ intrapF13  ] F14-own [ intrapF14  ] F15-own [
        intrapF15  ] F16-own [ intrapF16 ]
  F17-own [ intrapF17 ] F18-own [ intrapF18 ] F19-own [ intrapF19 ] F20-own [
        intrapF20 ]
```

Set Up Routine

++

```
to setup
ca

  ;; We check to make sure the file exists first
  ifelse ( file-exists? "File IO Ashley Patch Data.txt" )
  [
    ;; We are saving the data into a list, so it only needs to be loaded once.
    set patch-data []

    ;; This opens the file, so we can use it.
    file-open "File IO Ashley Patch Data.txt"

    ;; Read in all the data in the file
    while [ not file-at-end? ]
    [
      ;; file-read gives you variables.  In this case numbers.
      ;; We store them in a double list (ex [[1 1 9.9999] [1 2 9.9999] ...
      ;; Each iteration we append the next three-tuple to the current list
      set patch-data sentence patch-data (list (list file-read file-read file-read))
    ]

    print "File loading complete!"

    ;; Done reading in patch information.  Close the file.
```

```
    file-close
   ]
   [ user-message "There is no File IO Ashley Patch Data.txt file in current directory!" ]
  ;; This procedure will use the loaded in patch data to color the patches onto the screen.
  ;; The list is a list of three-tuples where the first item is the pxcor, the
  ;; second is the pycor, and the third is pcolor. Ex. [ [ 0 0 5 ] [ 1 34 26 ] ... ]

   cp ct
   ifelse ( is-list? patch-data )
     [ foreach patch-data [ set [pcolor] of patch first ? item 1 ? last ? ] ]
     [ user-message "You need to load in depth data first!" ]

   ifelse ( file-exists? "File IO Ashley Depth Data.txt" )
   [

     set depth-data []

     file-open "File IO Ashley Depth Data.txt"

     while [ not file-at-end? ]
     [
       set depth-data sentence depth-data (list (list file-read file-read file-read))
     ]

     print "File loading complete!"

      file-close
   ]
   [ user-message "There is no File IO Ashley Depth Data.txt file in current directory!" ]

    ifelse ( is-list? depth-data )
     [ foreach depth-data [ set [depth] of patch first ? item 1 ? last ? ] ]
     [ user-message "You need to load in depth data first!" ]

  clear-output
   clear-turtles clear-all-plots
   set week 0
   set year 0
   set mouse-clicked false
   set mouse-double-click false
   set clicked-turtle nobody
   set randomnumberlist []
   draw-walls
   set dead-turtles 0
   set dead-turtles-sal 0
   set dead-turtles-temp 0
```

```
 set dead-turtles-oxy 0
 set dead-turtles-pred 0
 set dead-turtles-dense 0
 set dead-turtles-disease-sal 0
 set dead-turtles-disease-temp 0
 set dead-turtles-disease-oxy 0
 set dead-turtles-disease-pred 0
 set dead-turtles-disease-dense 0
 set dead-turtles-trap 0
 set-default-shape T1 "adults"
 set-default-shape RT1 "adults"
 set-default-shape traps "circle"
 set-default-shape rectraps "box"


create-traps number-traps
 [set color white
       setxy 0
             random-float legal-limit - random-float (20 - legal-limit)
       if pcolor = 62 or pcolor = 68 [ randomize ]
      ask patch-here [ set pcolor yellow ]]

create-rectraps number-rectraps / 10
  [set color white
      setxy -3 (-17 + random-float 6)
      ask patch-here [ set pcolor orange ]]

create-rectraps number-rectraps / 10
  [set color white
      setxy 3 (-17 + random-float 6)
      ask patch-here [ set pcolor orange ]]

create-rectraps number-rectraps / 10
  [set color white
      setxy -3 (-11 + random-float 6)
      ask patch-here [ set pcolor orange ]]

create-rectraps number-rectraps / 10
  [set color white
      setxy 3 (-11 + random-float 6)
      ask patch-here [ set pcolor orange ]]

create-rectraps number-rectraps / 10
  [set color white
      setxy -2 (-3 + random-float 4)
      ask patch-here [ set pcolor orange ]]
```

```
  create-rectraps number-rectraps / 10
    [set color white
        setxy 2 (-3 + random-float 3)
        ask patch-here [ set pcolor orange ]]

  create-rectraps number-rectraps / 10
    [set color white
        setxy -2 (1 + random-float 3)
        ask patch-here [ set pcolor orange ]]

  create-rectraps number-rectraps / 10
    [set color white
        setxy 2 (1 + random-float 3)
        ask patch-here [ set pcolor orange ]]

   create-rectraps number-rectraps / 10
    [set color white
        setxy -1 (6 + random-float 6)
        ask patch-here [ set pcolor orange ]]

  create-rectraps number-rectraps / 10
    [set color white
        setxy 1 (6 + random-float 6)
        ask patch-here [ set pcolor orange ]]

 juvenile set-up
  set-default-shape J1 "crab"
  create-J1 initial-number-crabs * 0
    [set color 13
     set stage 1
     set hemato? false
     set natural-mortality (1 - (1 - exp (- predation-risk / 1)))
     set lowersalinity-tolerance LST + random 1 - random 1
     set uppersalinity-tolerance UST + random 1 - random 1
     set oxygen-tolerance OT + random 1 - random 1
     set lowertemperature-tolerance LTT + random 1 - random 1
     set uppertemperature-tolerance UTT + random 1 - random 1
     set age 1
     setxy random-float world-width
           random-float world-height
     if pcolor != 68 or pycor > -11
         [ randomize-recruit ]]

  set-default-shape J2 "crab"
  create-J2 initial-number-crabs * 0
```

```
  [set color 14
   set stage 2
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 2)))
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set age 3
   setxy random-float world-width
         random-float world-height
   if pcolor != 68 or pycor > -11
       [ randomize-recruit ]]

set-default-shape J3 "crab"
create-J3 initial-number-crabs * 0
  [set color 15
   set stage 3
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 3)))
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set age 6
   setxy random-float world-width
         random-float world-height
   if pcolor != 68 or pycor > -11
       [ randomize-recruit ]]

set-default-shape J4 "crab"
create-J4 initial-number-crabs * 6
  [set color 16
   set stage 4
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 4)))
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set age 10
   setxy random-float world-width
         random-float world-height
```

```
    if pcolor != 105 or pycor > 0
      [ randomize-juv ]]

  set-default-shape J5 "crab"
  create-J5 initial-number-crabs * 71
   [set color 17
    set stage 5
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 5)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 15
    setxy random-float world-width
        random-float world-height
    if pcolor != 105 or pycor > 0
      [ randomize-juv ]]

  set-default-shape J6 "crab"
  create-J6 initial-number-crabs * 239
   [set color 18
    set stage 6
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 6)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 21
    setxy random-float world-width
        random-float world-height
    if pcolor != 105 or pycor > 0
      [ randomize-juv ]]

  set-default-shape J7 "crab"
  create-J7 initial-number-crabs * 171
   [set color 23
    set stage 7
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 7)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
```

```
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 28
    setxy random-float world-width
        random-float world-height
    if pcolor != 105 or pycor > 0
      [ randomize-juv ]]

  set-default-shape J8 "crab"
  create-J8 initial-number-crabs * 167
   [set color 24
    set stage 8
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 8)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 36
    setxy random-float world-width
        random-float world-height
    if pcolor != 105 or pycor > 0
      [ randomize-juv ]]

  set-default-shape J9 "crab"
  create-J9 initial-number-crabs * 175
   [set color 25
    set stage 9
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 9)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 45
    setxy random-float world-width
        random-float world-height
    if pcolor != 105 or pycor > 0
      [ randomize-juv ]]

  set-default-shape J10 "crab"
  create-J10 initial-number-crabs * 79
   [set color 26
    set stage 10
```

```
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 10)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 55
    setxy random-float world-width
          random-float world-height
    if pcolor != 105 or pycor > 0
       [ randomize-juv ]]

 set-default-shape J11 "crab"
 create-J11 initial-number-crabs * 38
   [set color 27
    set stage 11
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 11)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set transition11 (random-float 1)
    set age 66
    setxy random-float world-width
          random-float world-height
    if pcolor != 105 or pycor > 0
       [ randomize-juv ]]

male set-up
 set-default-shape M12 "crab"
 create-M12 initial-number-crabs * 2
   [set color 91
    set stage 12
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 12)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapM12 random-float 1 - (1 / 20)
    set age 78
    setxy random-float world-width
```

```
        random-float world-height
    if pcolor != 105
      [ randomize ]]

  set-default-shape M13 "crab"
  create-M13 initial-number-crabs * 0
   [set color 92
    set stage 13
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 13)))
    set diseaseprob random-float 1
    set mortprob random-float 1
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapM13 random-float 1 - (1 / 19)
    set age 91
    setxy random-float world-width
        random-float world-height
    if pcolor != 105
      [ randomize ]]

  set-default-shape M14 "crab"
  create-M14 initial-number-crabs * 0
   [set color 93
    set stage 14
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 14)))
    set mortprob random-float 1
    set diseaseprob random-float 1
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapM14 random-float 1 - (1 / 18)
    set age 105
    setxy random-float world-width
        random-float world-height
    if pcolor != 105
      [ randomize ]]

  set-default-shape M15 "crab"
  create-M15 initial-number-crabs * 1
```

```
  [set color 94
   set stage 15
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 15)))
   set mortprob random-float 1
   set diseaseprob random-float 1
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set intrapM15 random-float 1 - (1 / 17)
   set age 120
   setxy random-float world-width
         random-float world-height
   if pcolor != 105
       [ randomize ]]

set-default-shape M16 "crab"
create-M16 initial-number-crabs * 2
  [set color 95
   set stage 16
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 16)))
   set mortprob random-float 1
   set diseaseprob random-float 1
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set intrapM16 random-float 1 - (1 / 16)
   set age 136
   setxy random-float world-width
         random-float world-height
   if pcolor != 105
       [ randomize ]]

set-default-shape M17 "crab"
create-M17 initial-number-crabs * 5
  [set color 96
   set stage 17
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 17)))
   set mortprob random-float 1
   set diseaseprob random-float 1
```

```
  set lowersalinity-tolerance LST + random 1 - random 1
  set uppersalinity-tolerance UST + random 1 - random 1
  set oxygen-tolerance OT + random 1 - random 1
  set lowertemperature-tolerance LTT + random 1 - random 1
  set uppertemperature-tolerance UTT + random 1 - random 1
  set intrapM17 random-float 1 - (1 / 15)
  set age 153
  setxy random-float world-width
      random-float world-height
  if pcolor != 105
     [ randomize ]]

set-default-shape M18 "crab"
create-M18 initial-number-crabs * 6
 [set color 97
  set stage 18
  set hemato? false
  set natural-mortality (1 - (1 - exp (- predation-risk / 18)))
  set mortprob random-float 1
  set diseaseprob random-float 1
  set lowersalinity-tolerance LST + random 1 - random 1
  set uppersalinity-tolerance UST + random 1 - random 1
  set oxygen-tolerance OT + random 1 - random 1
  set lowertemperature-tolerance LTT + random 1 - random 1
  set uppertemperature-tolerance UTT + random 1 - random 1
  set intrapM18 random-float 1 - (1 / 14)
  set age 171
  setxy random-float world-width
      random-float world-height
  if pcolor != 105
     [ randomize ]]

set-default-shape M19 "crab"
create-M19 initial-number-crabs * 5
 [set color 98
  set stage 19
  set hemato? false
  set natural-mortality (1 - (1 - exp (- predation-risk / 19)))
  set mortprob random-float 1
  set diseaseprob random-float 1
  set lowersalinity-tolerance LST + random 1 - random 1
  set uppersalinity-tolerance UST + random 1 - random 1
  set oxygen-tolerance OT + random 1 - random 1
  set lowertemperature-tolerance LTT + random 1 - random 1
  set uppertemperature-tolerance UTT + random 1 - random 1
  set intrapM19 random-float 1 - (1 / 13)
```

```
    set age 190
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

 set-default-shape M20 "crab"
 create-M20 initial-number-crabs * 6
   [set color 99
    set stage 20
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 20)))
    set mortprob random-float 1
    set diseaseprob random-float 1
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapM20 random-float 1 - (1 / 12)
    set age 210
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

female set-up
set-default-shape F12 "crab"
 create-F12 initial-number-crabs * 2
   [set color 51
    set stage 12
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 12)))
    set mortprob random-float 1
    set diseaseprob random-float 1
    set reproduction 0.05
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF12 random-float 1 + (1 / stage)
    set age 78
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
```

```
      [ randomize ]]

set-default-shape F13 "crab"
create-F13 initial-number-crabs * 0
  [set color 52
   set stage 13
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 13)))
   set mortprob random-float 1
   set diseaseprob random-float 1
   set reproduction 0.10
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set intrapF13 random-float 1 + (1 / stage)
   set age 91
   setxy random-float world-width
         random-float world-height
   if pcolor != 105
      [ randomize ]]

set-default-shape F14 "crab"
create-F14 initial-number-crabs * 0
  [set color 53
   set stage 14
   set hemato? false
   set natural-mortality (1 - (1 - exp (- predation-risk / 14)))
   set reproduction 0.15
   set lowersalinity-tolerance LST + random 1 - random 1
   set uppersalinity-tolerance UST + random 1 - random 1
   set oxygen-tolerance OT + random 1 - random 1
   set lowertemperature-tolerance LTT + random 1 - random 1
   set uppertemperature-tolerance UTT + random 1 - random 1
   set intrapF14 random-float 1 + (1 / stage)
   set age 105
   setxy random-float world-width
         random-float world-height
   if pcolor != 105
      [ randomize ]]

set-default-shape F15 "crab"
create-F15 initial-number-crabs * 1
  [set color 54
   set stage 15
```

```
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 15)))
    set reproduction 0.2
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF15 random-float 1 + (1 / stage)
    set age 120
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

set-default-shape F16 "crab"
create-F16 initial-number-crabs * 2
  [set color 55
    set stage 16
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 16)))
    set reproduction 0.25
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF16 random-float 1 + (1 / stage)
    set age 136
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

set-default-shape F17 "crab"
create-F17 initial-number-crabs * 5
  [set color 56
    set stage 17
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 17)))
    set reproduction 0.30
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
```

```
    set intrapF17 random-float 1 + (1 / stage)
    set age 153
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

 set-default-shape F18 "crab"
 create-F18 initial-number-crabs * 6
   [set color 57
    set stage 18
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 18)))
    set reproduction 0.35
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF18 random-float 1 + (1 / stage)
    set age 171
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

 set-default-shape F19 "crab"
 create-F19 initial-number-crabs * 5
   [set color 58
    set stage 19
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 19)))
    set mortprob random-float 1
    set diseaseprob random-float 1
    set reproduction 0.40
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF19 random-float 1 + (1 / stage)
    set age 190
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]
```

```
 set-default-shape F20 "crab"
 create-F20 initial-number-crabs * 6
   [set color 59
    set stage 20
    set hemato? false
    set natural-mortality (1 - (1 - exp (- predation-risk / 20)))
    set reproduction 0.45
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF20 random-float 1 + (1 / stage)
    set age 210
    setxy random-float world-width
          random-float world-height
    if pcolor != 105
        [ randomize ]]

 set summermove [ 1 ]
 set wintermove [ 1 ]
 set spfallmove [ 1 ]

 ask turtles [ set message? false ]

end
;;+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
           ++++++++++++++++++++++++++++++

to randomize
  setxy random-float world-width
        random-float world-height
  if pcolor != 105
        [ randomize ]
end

to randomize-recruit
  setxy random-float world-width
        random-float world-height
  if pcolor != 68 or pycor > -9
        [ randomize-recruit ]
end

to randomize-juv
  setxy random-float world-width
```

```
        random-float world-height
  if pcolor != 105 or pycor > 0
        [ randomize-juv ]
end

to draw-walls
 ; draw top and bottom walls
  ask patches with [pycor = max-pycor]
    [ set pcolor 62 ]
end

to generate-number
  set potnumber random number-traps + 1
  if member? potnumber randomnumberlist = true
  [generate-number]
end
```

Go Routine

```
*****************************************************************************
********
to go
  if week > 15 and week < 39 [ create-J1 ((immigration * 0.8) + (immigration * 0.2))
   [set breed J1
    set color white
    set stage 1
    set natural-mortality (1 - (1 - exp (- predation-risk / 1)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 1
    set hemato? false
    setxy random-float world-width
          random-float world-height]]


 move-turtles

 change

 move-traps

 do-plot
```

```
 ask turtles [ set age age + 1 ]

 set week (week + 1)
   if week = 52 [ set year (year + 1) ]
   if week = 52 [
   set week 0
   set dead-turtles 0
   set dead-turtles-sal 0
   set dead-turtles-temp 0
   set dead-turtles-oxy 0
   set dead-turtles-pred 0
   set dead-turtles-dense 0
   set dead-turtles-disease 0
   set dead-turtles-disease-sal 0
   set dead-turtles-disease-temp 0
   set dead-turtles-disease-oxy 0
   set dead-turtles-disease-pred 0
   set dead-turtles-disease-dense 0
   set dead-turtles-trap 0
   set dead-turtles-trap-disease 0
   ask T1 [die]
   ask RT1 [die]]
end
;;*********************************************************************
            **********************


to move-turtles
 ask patches [if not (pcolor  = 62)
               [ set temperature tempchange + ((20.10335685414452 + 9.252440403517787 *
            SIN((6.2831853071795864770 * week / 52.31852753497177 +
            4.219426474725649) * 180 / pi)))]]
 ask patches [if not (pcolor = 62)
               [ set oxygen oxygenchange + (12.87399448655169 * EXP(- temperature /
            20.86073401199412))]]
 ask patches [if not (pcolor  = 62)
               [ set flow flowchange + ((3.365195488738337 + 0.1407961432286253 *
            SIN((6.2831853071795864770 * week / 52.31852753497177 +
            0.47736484692314) * 180 / pi)))]]
 ask patches [if not (pcolor = 62)
               [ set salinity salinitychange + ((33.0615344685663 / (1 + EXP(-((pycor + ((flow
            - 2.6) * 12)) - (-0.48049)) / (-4.1216 + flow - 2.6)))))]]
 colors

  ask J1 [ without-interruption
  [ ifelse pycor < 15
```

```
 [ set heading (0 + random-float 90 - random-float 90)]
 [set heading (random-float 360)]
 ifelse [pcolor] of patch-ahead 1 != 68 or abs [pycor] of patch-ahead 1 = max-pycor
 [set heading (180 - heading)]
 [fd 1]]]


 ask J2 [ without-interruption
 [ ifelse pycor < 15
 [ set heading (0 + random-float 90 - random-float 90)]
 [set heading (random-float 360)]
 ifelse [pcolor] of patch-ahead 1 != 68 or abs [pycor] of patch-ahead 1 = max-pycor
 [set heading (180 - heading)]
 [fd 1]]]

 ask J3 [ without-interruption
 [ ifelse pycor < 15
 [ set heading (0 + random-float 90 - random-float 90)]
 [set heading (random-float 360)]
 ifelse [pcolor] of patch-ahead 1 != 68 or abs [pycor] of patch-ahead 1 = max-pycor
 [set heading (180 - heading)]
 [fd 1]]]

 ask J4 [ juvmove ]

 ask J5 [ juvmove ]

 ask J6 [ juvmove ]

 ask J7 [ juvmove ]

 ask J8 [ juvmove ]

 ask J9 [ juvmove ]

 ask J10 [ juvmove ]

 ask J11 [ juvmove ]

ask M12 [

 ifelse  pcolor = yellow and intrapM12 < trapping-probability [ trapped ]
 [ malemove ]
 ifelse pcolor = orange and intrapM12 < rectrapping-probability [ rectrapped ]
 [ malemove ]]
```

```
 ask M13 [
 ifelse  pcolor = yellow and intrapM13 < trapping-probability [ trapped ]
 [ malemove ]
   ifelse pcolor = orange and intrapM13 < rectrapping-probability [ rectrapped ]
 [ malemove ] ]

 ask M14 [
 ifelse pcolor = yellow and intrapM14 < trapping-probability [ trapped ]
[ malemove ]
  ifelse pcolor = orange and intrapM14 < rectrapping-probability [ rectrapped ]
 [ malemove ]]

 ask M15 [
ifelse pcolor = yellow and intrapM15 < trapping-probability [ trapped ]
[ malemove ]
  ifelse pcolor = orange and intrapM15 < rectrapping-probability [ rectrapped ]
 [ malemove ]]

 ask M16 [
 ifelse pcolor = yellow and intrapM16 < trapping-probability [ trapped ]
 [ malemove ]
   ifelse pcolor = orange and intrapM16 < rectrapping-probability [ rectrapped ]
 [ malemove ]]

 ask M17 [
 ifelse pcolor = yellow and intrapM17 < trapping-probability [ trapped ]
[ malemove ]
  ifelse pcolor = orange and intrapM17 < rectrapping-probability [ rectrapped ]
 [ malemove ]]

 ask M18 [
 ifelse pcolor = yellow and intrapM18 < trapping-probability [ trapped ]
 [ malemove ]
   ifelse pcolor = orange and intrapM18 < rectrapping-probability [ rectrapped ]
 [ malemove ]]

 ask M19 [
 ifelse pcolor = yellow and intrapM19 < trapping-probability [ trapped ]
[ malemove ]
  ifelse pcolor = orange and intrapM19 < rectrapping-probability [ rectrapped ]
 [ malemove ]]

 ask M20 [
 ifelse pcolor = yellow and intrapM20 < trapping-probability [ trapped ]
[ malemove ]
  ifelse pcolor = orange and intrapM20 < rectrapping-probability [ rectrapped ]
```

```
 [ malemove ]]

ask F12 [
 ifelse pcolor = yellow and intrapF12 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
[ femalemove ]
  ifelse pcolor = orange and intrapF12 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
 [ femalemove ]]

 ask F13 [
 ifelse pcolor = yellow and intrapF13 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
 [ femalemove ]
    ifelse pcolor = orange and intrapF13 < rectrapping-probability and (week < 16 or
          week > femrectrapweek) [ rectrapped ]
 [ femalemove ]]

 ask F14 [
 ifelse pcolor = yellow and intrapF14 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
[ femalemove ]
  ifelse pcolor = orange and intrapF14 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
 [ femalemove ]]

 ask F15 [
 ifelse pcolor = yellow and intrapF15 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
[ femalemove ]
   ifelse pcolor = orange and intrapF15 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
 [ femalemove ]]

 ask F16 [
 ifelse pcolor = yellow and intrapF16 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
[ femalemove ]
   ifelse pcolor = orange and intrapF16 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
 [ femalemove ]]

 ask F17 [
 ifelse pcolor = yellow and intrapF17 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
[ femalemove ]
```

```
    ifelse pcolor = orange and intrapF17 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
  [ femalemove ]]

  ask F18 [
  ifelse  pcolor = yellow and intrapF18 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
 [ femalemove ]
    ifelse pcolor = orange and intrapF18 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
  [ femalemove ]]

  ask F19 [
  ifelse  pcolor = yellow and intrapF19 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
[ femalemove ]
   ifelse pcolor = orange and intrapF19 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
  [ femalemove ]]

  ask F20 [
    ifelse pcolor = yellow and intrapF20 < trapping-probability and (week < 16 or week >
          femtrapweek) [ trapped ]
 [ femalemove ]
    ifelse pcolor = orange and intrapF20 < rectrapping-probability and (week < 16 or week
          > femrectrapweek) [ rectrapped ]
  [ femalemove ]]

end

to juvmove

if week > -1 and week < 13 [
  without-interruption [
   ifelse salinity > (stage + random-float 3 - random-float 3) and [pcolor] of patch-at-
          heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
          patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]

if week > 12 and week < 52 [
   without-interruption [
```

```
   ifelse salinity > (25 + random-float 3 - random-float 3) and [pcolor] of patch-at-
          heading-and-distance 0 1 = 105
     [set heading (180 + random-float 90 - random-float 90)]
     [set heading (0 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
          patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]
end

to malemove

 if week > -1 and week < 13 [
  without-interruption [
   ifelse salinity > (0.6423 * stage + 0.9951 + random-float 3 - random-float 3) and
          [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
          patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]

 if week > 12 and week < 26 [
   without-interruption [
   ifelse salinity > (-1.525 * stage + 35.225 + random-float 3 - random-float 3) and
          [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
          patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]

 if week > 25 and week < 39 [
   without-interruption [
   ifelse salinity > (-0.9825 * stage + 30.807 + random-float 3 - random-float 3) and
          [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
          patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]

if week > 38 and week < 52 [
```

```
   without-interruption [
   ifelse salinity > (0.1 * stage + 21.867 + random-float 3 - random-float 3) and [pcolor]
         of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
         patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]
end

to femalemove

if week > -1 and week < 13 [
  without-interruption [
   ifelse salinity > (1.8741 * stage - 10.427 + random-float 3 - random-float 3) and
         [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
         patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]

 if week > 12 and week < 26 [
   without-interruption [
   ifelse salinity > (-0.324 * stage + 26.856 + random-float 3 - random-float 3) and
         [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
         patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]

 if week > 25 and week < 39 [
   without-interruption [
   ifelse salinity > (0.0035 * stage + 24.804 + random-float 3 - random-float 3) and
         [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
         patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]
```

```
if week > 38 and week < 52 [
   without-interruption [
   ifelse salinity > (-0.2615 * stage + 28.726 + random-float 3 - random-float 3) and
            [pcolor] of patch-at-heading-and-distance 0 1 = 105
     [set heading (0 + random-float 90 - random-float 90)]
     [set heading (180 + random-float 90 - random-float 90)]
   ifelse [pcolor] of patch-ahead 1 = 62 or [pcolor] of patch-ahead 1 = 68 or abs [pycor] of
            patch-ahead 1 = max-pycor
     [set heading (180 - heading)]
     [fd 1]]]
end

to change

 ask J1 [
  death
  disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 1)
    [ set breed J2
    set color 14
    set stage 2
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 2)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J2 [
  death
  disease
   if (1 - (temperature / 29)) + random-float 2  < (age / 3)
    [ set breed J3
    set color 15
    set stage 3
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 3)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J3 [
 death
```

```
 disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 6)
    [set breed J4
    set color 16
    set stage 4
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 4)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J4 [
 death
 disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 10)
    [ set breed J5
    set color 17
    set stage 5
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 5)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J5 [
 death
 disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 15)
    [ set breed J6
    set color 18
    set stage 6
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 6)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J6 [
 death
 disease
```

```
   if (1 - (temperature / 29)) + random-float 2  < (age / 21)
    [ set breed J7
    set color 23
    set stage 7
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 7)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J7 [
 death
 disease
   if (1 - (temperature / 29))  + random-float 2 < (age / 28)
    [ set breed J8
    set color 24
    set stage 8
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 8)))
    set mortprob random-float 1
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J8 [
 death
 disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 36)
    [ set breed J9
    set color 25
    set stage 9
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 9)))
    set mortprob random-float 1
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J9 [
 death
```

```
 disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 45)
    [ set breed J10
    set color 26
    set stage 10
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 10)))
    set mortprob random-float 1
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J10 [
 death
 disease
   if (1 - (temperature / 29))  + random-float 2  < (age / 55)
    [ set breed J11
    set color 27
    set stage 11
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 11)))
    set mortprob random-float 1
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance]]

ask J11 [
  set transition11 (random-float 1)
  death
  disease
   ifelse (1 - (temperature / 29))  + random-float 2  < (age / 66) and transition11 > 0.50
    [ set breed M12
    set color 91
    set stage 12
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 12)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM12 random-float 1 - (1 / 20) ]
```

```
   [ if (1 - (temperature / 29))  + random-float 2  < (age / 66) and transition11 < 0.50
   [ set breed F12
    set color 51
    set stage 12
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 12)))
    set reproduction 0.05
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set intrapF12 random-float 1 + (1 / stage)]]]

ask M12 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 78)
    [ set breed M13
    set color 92
    set stage 13
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 13)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM13 random-float 1 - (1 / 19)]]

ask M13 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 91)
    [ set breed M14
    set color 93
    set stage 14
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 14)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM14 random-float 1 - (1 / 18)]]
```

```
ask M14 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 105)
    [ set breed M15
    set color 94
    set stage 15
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 15)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM15 random-float 1 - (1 / 17)]]

ask M15 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 120)
    [ set breed M16
    set color 95
    set stage 16
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 16)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM16 random-float 1 - (1 / 16)]]

ask M16 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 136)
    [ set breed M17
    set color 96
    set stage 17
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 17)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
```

```
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM17 random-float 1 - (1 / 15)]]

ask M17 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 153)
    [ set breed M18
    set color 97
    set stage 18
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 18)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM18 random-float 1 - (1 / 14)]]

ask M18 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 171)
    [ set breed M19
    set color 98
    set stage 19
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 19)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM19 random-float 1 - (1 / 13)]]

ask M19 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 190)
    [ set breed M20
    set color 99
    set stage 20
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 20)))
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
```

```
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapM20 random-float 1 - (1 / 12)]]
ask M20 [
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 220)
      [ifelse hemato? = true
        [ set dead-turtles-disease dead-turtles-disease + 1 die]
        [ set dead-turtles dead-turtles + 1 die]
      ]]

ask F12 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 78)
    [ set breed F13
    set color 52
    set stage 13
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 13)))
    set reproduction 0.10
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapF13 random-float 1 - (1 / stage)]]

ask F13 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 91)
    [ set breed F14
    set color 53
    set stage 14
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 14)))
    set reproduction 0.15
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
```

```
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapF14 random-float 1 - (1 / stage)]]

ask F14 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 105)
    [ set breed F15
    set color 54
    set hemato? hemato?
    set stage 15
    set natural-mortality (1 - (1 - exp (- predation-risk / 15)))
    set reproduction 0.20
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapF15 random-float 1 - (1 / stage)]]

ask F15 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 120)
    [ set breed F16
    set color 55
    set stage 16
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 16)))
    set reproduction 0.25
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapF16 random-float 1 - (1 / stage)]]

ask F16 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 136)
    [ set breed F17
    set color 56
```

```
      set stage 17
      set hemato? hemato?
      set natural-mortality (1 - (1 - exp (- predation-risk / 17)))
      set reproduction 0.30
      set lowersalinity-tolerance lowersalinity-tolerance
      set uppersalinity-tolerance uppersalinity-tolerance
      set oxygen-tolerance oxygen-tolerance
      set lowertemperature-tolerance lowertemperature-tolerance
      set uppertemperature-tolerance uppertemperature-tolerance
      set intrapF17 random-float 1 - (1 / stage)]]

 ask F17 [
  birth
  disease
  death
    if (1 - (temperature / 29))  + random-float 2  < (age / 153)
     [ set breed F18
      set color 57
      set stage 18
      set hemato? hemato?
      set natural-mortality (1 - (1 - exp (- predation-risk / 18)))
      set reproduction 0.35
      set lowersalinity-tolerance lowersalinity-tolerance
      set uppersalinity-tolerance uppersalinity-tolerance
      set oxygen-tolerance oxygen-tolerance
      set lowertemperature-tolerance lowertemperature-tolerance
      set uppertemperature-tolerance uppertemperature-tolerance
      set intrapF18 random-float 1 - (1 / stage)]]

 ask F18 [
  birth
  disease
  death
    if (1 - (temperature / 29))  + random-float 2  < (age / 171)
     [ set breed F19
      set color 58
      set stage 19
      set hemato? hemato?
      set natural-mortality (1 - (1 - exp (- predation-risk / 19)))
      set reproduction 0.40
      set lowersalinity-tolerance lowersalinity-tolerance
      set uppersalinity-tolerance uppersalinity-tolerance
      set oxygen-tolerance oxygen-tolerance
      set lowertemperature-tolerance lowertemperature-tolerance
      set uppertemperature-tolerance uppertemperature-tolerance
      set intrapF19 random-float 1 - (1 / stage)]]
```

```
ask F19 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 190)
    [ set breed F20
    set color 59
    set stage 20
    set hemato? hemato?
    set natural-mortality (1 - (1 - exp (- predation-risk / 20)))
    set reproduction 0.45
    set lowersalinity-tolerance lowersalinity-tolerance
    set uppersalinity-tolerance uppersalinity-tolerance
    set oxygen-tolerance oxygen-tolerance
    set lowertemperature-tolerance lowertemperature-tolerance
    set uppertemperature-tolerance uppertemperature-tolerance
    set intrapF20 random-float 1 - (1 / stage)]]

ask F20 [
 birth
 disease
 death
   if (1 - (temperature / 29))  + random-float 2  < (age / 220)
      [ifelse hemato? = true
        [ set dead-turtles-disease dead-turtles-disease + 1 die]
        [ set dead-turtles dead-turtles + 1 die]
      ]]
 end



to trapped
   set breed T1
   set size 1
   set shape "crab"
     set color gray
   ifelse hemato? = true
     [set dead-turtles-trap-disease dead-turtles-trap-disease + 1]
     [set dead-turtles-trap dead-turtles-trap + 1]
   stop
 end

to rectrapped
   set breed RT1
   set size 1
```

```
   set shape "crab"
     set color gray
   ifelse hemato? = true
     [set dead-turtles-trap-disease dead-turtles-trap-disease + 1]
     [set dead-turtles-trap dead-turtles-trap + 1]
   stop
 end


to death
  ifelse hemato? = false
    [set saltprob random-float 1
    set tempprob random-float 1
    set oxyprob random-float 1
    set mortprob random-float 1
    set denseprob random-float 1]
    [set saltprob 1 + random-float 1
    set tempprob 1 + random-float 1
    set oxyprob 1 + random-float 1
    set mortprob 1 + random-float 1
    set denseprob 1 + random-float 1]

 if salt? [
    if salinity < lowersalinity-tolerance + random-float 1 - random-float 1
      [if (saltprob + (1 / (1 + salinity))) > random-float 35
        [ifelse hemato? = false
          [set dead-turtles-sal dead-turtles-sal + 1
          die]
          [set dead-turtles-disease-sal dead-turtles-disease-sal + 1
          die]]]
    if salinity > uppersalinity-tolerance + random-float 1 - random-float 1
      [if (saltprob + (1 / (36 - salinity))) > random-float 25
        [ifelse hemato? = false
          [set dead-turtles-sal dead-turtles-sal + 1
          die]
          [set dead-turtles-disease-sal dead-turtles-disease-sal + 1
          die]]]]
  if temp? [
    if temperature < lowertemperature-tolerance
      [if (tempprob + (1 / (temperature - 10))) > random-float 25
        [ifelse hemato? = false
          [set dead-turtles-temp dead-turtles-temp + 1
          die]
          [set dead-turtles-disease-temp dead-turtles-disease-temp + 1
          die]]]
    if temperature > uppertemperature-tolerance
```

```
    [if tempprob + (1 / (36 - temperature)) > random-float 25
      [ifelse hemato? = false
        [set dead-turtles-temp dead-turtles-temp + 1
        die]
        [set dead-turtles-disease-temp dead-turtles-disease-temp + 1
        die]]]]

 if oxy? [
   if oxygen < oxygen-tolerance
    [if (oxyprob + (1 / (0.01 + oxygen))) > random-float 25
      [ifelse hemato? = false
        [set dead-turtles-oxy dead-turtles-oxy + 1
        die]
        [set dead-turtles-disease-oxy dead-turtles-disease-oxy + 1
        die]]]]
  if nat-mort? [
   if (mortprob + (1 / (1 + salinity))) > (natural-mortality * random-float 25)
      [ifelse hemato? = false
        [set dead-turtles-pred dead-turtles-pred + 1
        die]
        [set dead-turtles-disease-pred dead-turtles-disease-pred + 1
        die]]]
  if dense? [
   set other-turtle one-of other turtles-here
    if other-turtle != nobody [
      if [natural-mortality] of other-turtle < natural-mortality [
        if denseprob + (count turtles-here / carrying-capacity) > (natural-mortality *
          random-float 100)
          [ifelse hemato? = false
            [set dead-turtles-dense dead-turtles-dense + 1
            die]
            [set dead-turtles-disease-dense dead-turtles-disease-dense + 1
            die]]]]]
end

to birth
  set repro random-float 1
  if reproduction > repro and (week > 15 and week < 39)
   [ hatch ((births * 0.90) + (births * random-float 0.2))
   [set breed J1
    set color white
    set stage 1
    set natural-mortality (1 - (1 - exp (- predation-risk / 1)))
    set lowersalinity-tolerance LST + random 1 - random 1
    set uppersalinity-tolerance UST + random 1 - random 1
    set oxygen-tolerance OT + random 1 - random 1
```

```
    set lowertemperature-tolerance LTT + random 1 - random 1
    set uppertemperature-tolerance UTT + random 1 - random 1
    set age 1
    setxy random-float world-width
          random-float world-height
    if pcolor != 68 or pycor > -11
       [ randomize-recruit ]
    set hemato? false]]
end

to disease
  set diseaseprob random-float 1
  if breed != traps [
  if breed != t1 [
  ifelse (count turtles-here - count traps-here - count t1-here) * disease-transmission * (1 /
          (36 - salinity))  > diseaseprob * random-float 500
     [set hemato? true]
     [set hemato? false]]]
end

to move-traps
  ask traps [
    ask patch-here [ set pcolor 105]
    if random-float 1 > 0.90 [
    ifelse pycor > (temperature - 25) [set heading 180 forward random-float 4]
                                      [set heading 0 forward random-float 8]]]
  ask traps [
    ask patch-here [ set pcolor yellow ]]
end

to colors
ask patches [ if tempcolor? [
              if temperature > 7.5 and temperature <= 10 [ set pcolor 19.9 ]
              if temperature > 10 and temperature <= 12.5 [ set pcolor 19 ]
              if temperature > 12.5 and temperature <= 15 [ set pcolor 18 ]
              if temperature > 15 and temperature <= 17.5 [ set pcolor 17 ]
              if temperature > 17.5 and temperature <= 20 [ set pcolor 16 ]
              if temperature > 20 and temperature <= 22.5 [ set pcolor 15 ]
              if temperature > 22.5 and temperature <= 25 [ set pcolor 14 ]
              if temperature > 25 and temperature <= 27.5 [ set pcolor 13 ]
              if temperature > 27.5 and temperature <= 30 [ set pcolor 12 ]
              if temperature > 30 [ set pcolor 11 ]
                ]]

ask patches [ if saltcolor? [
              if salinity > 0 and salinity <= 5 [ set pcolor 49 ]
```

```
            if salinity > 5 and salinity <= 10 [ set pcolor 48 ]
            if salinity > 10 and salinity <= 15 [set pcolor 47 ]
            if salinity > 15 and salinity <= 20 [ set pcolor 46]
            if salinity > 20 and salinity <= 25 [ set pcolor 45]
            if salinity > 25 and salinity <= 30 [ set pcolor 44 ]
            if salinity > 30 and salinity <= 35 [ set pcolor 43 ]
            if salinity > 35 and salinity <= 40 [ set pcolor 42 ]
            if salinity > 40 [ set pcolor 41 ]
            ]]

ask patches [ if oxycolor? [
            if oxygen > 0 and oxygen <= 1 [set pcolor 61 ]
            if oxygen > 1 and oxygen <= 2 [ set pcolor 62 ]
            if oxygen > 2 and oxygen <= 3 [ set pcolor 63 ]
            if oxygen > 3 and oxygen <= 4 [ set pcolor 64 ]
            if oxygen > 4 and oxygen <= 5 [ set pcolor 65 ]
            if oxygen > 5 and oxygen <= 6 [ set pcolor 66 ]
            if oxygen > 6 and oxygen <= 7 [ set pcolor 67 ]
            if oxygen > 7 and oxygen <= 8 [ set pcolor 68 ]
            if oxygen > 8 [ set pcolor 69 ]
            ]]

ask patches [ if depthcolor? [
            if depth <= 0 [set pcolor 34]
            if depth > 0 and depth <= 1 [set pcolor 97]
            if depth > 1 and depth <= 2 [set pcolor 96]
            if depth > 2 and depth <= 3 [set pcolor 95]
            if depth > 3 and depth <= 5 [set pcolor 94]
            if depth > 5 and depth <= 10 [set pcolor 93]
            if depth > 10 [set pcolor 92]
            ]]

ask patches [ if flowcolor? [
            if depth <= 0 [set pcolor 62]
            if flow > 2.5 and flow <= 2.7 [set pcolor 29]
            if flow > 2.7 and flow <= 2.9 [set pcolor 28]
            if flow > 2.9 and flow <= 3.1 [set pcolor 27]
            if flow > 3.1 and flow <= 3.3 [set pcolor 26]
            if flow > 3.3 and flow <= 3.5 [set pcolor 25]
            if flow > 3.5 and flow <= 3.7 [set pcolor 24]
            if flow > 3.7 and flow <= 3.9 [set pcolor 23]
            if flow > 3.9 and flow <= 4.1 [set pcolor 22]
            if flow > 4.1 [set pcolor 21]
            ]]end
```

```
to do-plot
  set-current-plot "Populations"
  set-current-plot-pen "J1"
  plot log (count J1 + 1) 10
  set-current-plot-pen "J2"
  plot log (count J2 + 1) 10
  set-current-plot-pen "J3"
  plot log (count J3 + 1) 10
  set-current-plot-pen "J4"
  plot log (count J4 + 1) 10
  set-current-plot-pen "J5"
  plot log (count J5 + 1) 10
  set-current-plot-pen "J6"
  plot log (count J6 + 1) 10
  set-current-plot-pen "J7"
  plot log (count J7 + 1) 10
  set-current-plot-pen "J8"
  plot log (count J8 + 1) 10
  set-current-plot-pen "J9"
  plot log (count J9 + 1) 10
  set-current-plot-pen "J10"
  plot log (count J10 + 1) 10
  set-current-plot-pen "J11"
  plot log (count J11 + 1) 10
  set-current-plot-pen "M12"
  plot log (count M12 + 1) 10
  set-current-plot-pen "M13"
  plot log (count M13 + 1) 10
  set-current-plot-pen "M14"
  plot log (count M14 + 1) 10
  set-current-plot-pen "M15"
  plot log (count M15 + 1) 10
  set-current-plot-pen "M16"
  plot log (count M16 + 1) 10
  set-current-plot-pen "M17"
  plot log (count M17 + 1) 10
  set-current-plot-pen "M18"
  plot log (count M18 + 1) 10
  set-current-plot-pen "M19"
  plot log (count M19 + 1) 10
  set-current-plot-pen "M20"
  plot log (count M20 + 1) 10
   set-current-plot-pen "F12"
  plot log (count F12 + 1) 10
```

```
  set-current-plot-pen "F13"
  plot log (count F13 + 1) 10
  set-current-plot-pen "F14"
  plot log (count F14 + 1) 10
  set-current-plot-pen "F15"
  plot log (count F15 + 1) 10
  set-current-plot-pen "F16"
  plot log (count F16 + 1) 10
  set-current-plot-pen "F17"
  plot log (count F17 + 1) 10
  set-current-plot-pen "F18"
  plot log (count F18 + 1) 10
  set-current-plot-pen "F19"
  plot log (count F19 + 1) 10
  set-current-plot-pen "F20"
  plot log (count F20 + 1) 10

end
```