Forecasting the South Carolina Blue Crab Fishery Using Real-Time Freshwater Flow Data

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EXECUTIVE SUMMARY

Blue crabs are one of the most important commercial fisheries in the US but have been on the decline over the past 20 years. From 1998 to 2014, the annual landings of blue crabs in South Carolina declined by over 48% from 7.4 to 3.8 million pounds (approximately $5.4 million dollars annually). This decline does not appear to be associated with an increase in fishing effort as the number of commercial licenses remained relatively constant during this same period. There is, however, a strong positive correlation between annual landings and annual freshwater discharge. Decreases in freshwater discharge due to persistent drought and increasing demand from agriculture and human consumption has led to changes in the salinity profiles of South Carolina salt marshes. A recently-completed four-year field study of blue crabs in the ACE Basin National Estuarine Research Reserve identified several key life history stages influenced by these changes in salinity. In this project, I integrated these empirical findings into a spatially-explicit, individual-based population model (IBM) to forecast the consequences of future changes in freshwater discharge on the abundance, distribution, health, commercial landings, and economic value of the blue crab fishery.

A seventy-five year historical record of river discharge data from the Givhans Ferry, SC gaging station (USGS #02175000) was used to inform future river discharge trends using an autoregressive integrated moving average (ARIMA) with a seasonal exponential smoothing function and 12 year return period. The forecasted river discharge levels were within previously observed ranges of high and low flow with drought periods at or slightly above those of the 2002 drought of record. Monthly river discharge levels, both historical and forecasted were then used as input parameters for the SCBCRABS-ACE spatially-explicit individual-based population model for blue crabs. Model runs were initiated with historical river discharge levels from 1990 to 2013 and ARIMA model forecasted discharge levels from 2014-2040. Thus, the IBM model used 24 years of observed historical river discharge data and 26 years of forecasted river discharge data. Changes in river flow only influence the salinity profile of habitat patches within the model. Fishing effort, water temperature, sea level, pH, dissolved oxygen, predator density and crab food availability were assumed to be constant during the 50 year simulations. In the IBM salinity influences multiple crab life history parameters including crab movement direction, probability of infection by parasites, probability of predation, and low and high salinity mortality due to osmotic stress. Thus, the model isolates the net influence of altered salinity profiles in a typical Southeastern US estuary under future scenarios of freshwater discharge.

To calibrate the IBM model landings to the SC commercial landings, model output from the time period of 1990-2013 were compared to the observed commercial landings for that same time period. The median model catch from 100 runs of the model was then aligned with the median commercial catch so the forecasted landings could be reported in millions lbs. landed per year. The SCBCRABS forecast of crab landings were below the actual observed landings for the period of 1990-1999, but from the period of 2000-2013, observed landings were typically within on SD of the forecasted landings. The model predicted stability in the landings in the near term with the potential for slight gains over the next decade (0.1-1.3 million pounds per year). However, the model also predicts that with the next severe drought, blue crabs will once again decline at a rate of (0.25 million pounds per year) and continue to do so if river discharge levels are unable to return to a critical minimum of 1250 cf/s. When this critical level is reached once during a three year period, crab landings stop increasing and remained steady. When this critical level is reached twice during a three year period, crab landings decrease. And when this critical level was reached thrice during a three year period, crab landings decline severely. These effects of perturbation persist for up to five years before the population returns to stable annual landings.

Results of this model were shared with climate scientists, marine scientists, and fisheries managers at both regional and national conferences and by webinar. A website and Facebook group was constructed to disseminate the model forecasts to fishermen and resource manages and to provide a mechanism to regularly update the model results as new data becomes available. A complete summary of blue crab life history, the SCBCRABS model, and the SC blue crab fisheries forecast can be found the SC Blue Crab Forecast Webpage (http://scbcrabs.blogspot.com) along with a recorded video presentation of the model and future SC blue crab forecast.

PROJECT PARTNERS AND FUNDING AMOUNTS

SC SeaGrant – R/SC 10 – M.J. Childress and E. Wenner
South Carolina Blue Crab Regional Abundance Biotic Simulation
$137,068 – 3/1/2004 – 2/28/2006

SC SeaGrant – R/CF 15 – M.J. Childress
Drought and the decline of blue crab in South Carolina
$ 98,396 – 2/1/2010 – 1/31/2012

Carolinas Integrated Sciences and Assessments – M.J. Childress, K. Dow, K. Lackstrom
Forecasting the South Carolina blue crab fishery using real-time freshwater flow data
$ 0 – 1/1/2013 – 12/31/2015

National Integrated Drought Information Service – UCAR Z14-15056 – M.J. Childress
Forecasting the South Carolina blue crab fishery using real-time freshwater flow data
$ 24,550 – 4/16/2014 – 6/30/2015

PROJECT START AND COMPLETION DATES

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Final report: 8/31/2015

PROJECT ACTIVITIES AND METHODOLOGIES

Introduction

Most of the world's estuaries and coastal seas are in serious decline due multiple anthropogenic stressors. These stressors include overfishing, habitat loss, and climate-induced changes in sea-level, warming, acidification, and drought (Lotze et al. 2006). Of these stressors, drought is one of the first to be positively linked to declines in salt marsh vegetation and commercially important species (Gilbert et al. 2012). Marine resource managers primarily rely on regulating harvest effort, gear types, seasonal closures, and area closures (Rosenberg et al. 2006), but rarely are do they consider climate variables. In part, this is due to a feeling that climate variables are beyond the control of fisheries managers, but may also be due to the lack of predictive forecast models that link climate variables to fisheries landings (Harley et al. 2006). What are needed are models that utilize currently-available climate data to forecast water quality conditions known to influence the abundance and distribution of fisheries species and fishing effort.

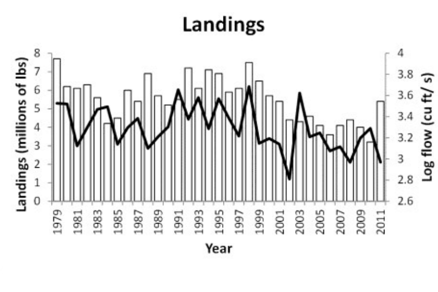

Figure 1. SC commercial blue crab landings (bars) compared to the annual discharge of the Edisto River (line). Discharge is positively correlated with landings (r = 0.33, p = 0.034).

The Atlantic blue crab, *Callinectes sapidus*, is one of the most important commercial fisheries in the US, but is in serious decline. This decline has been linked to overfishing (Lipcius and Stockhausen 2002), habitat loss (Hovel and Lipcius 2002), and increasing disease (Messick and Shields 2000). But recent drastic declines in crab numbers during the severe drought of 2002, suggests that climate change may have a direct influence on the health of this commercial fishery (Lee and Frischer 2004). In South Carolina, there has been a 48% decline in annual commercial landings from 1998 (7.4 million pounds) to 2014 (3.8 million pounds). However, there is little evidence that fishing effort has increased much since 1998. There is evidence, however, that annual landings are positively correlated with freshwater discharge into South Carolina salt marshes (Figure 1). Furthermore, a four-year study of blue crab abundance and distribution in the ACE Basin National Estuarine Research Reserve has found significant correlations between river discharge and salinity, and between salinity and crab survival, predation and disease (Figure 2 – Childress and Parmenter 2012; Parmenter 2012; Parmenter et al. 2013).

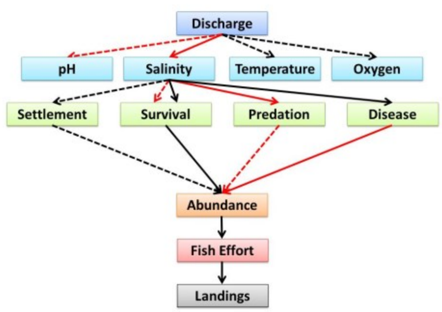

Figure 2. Correlations between river discharge, water quality measures, life history traits, and abundance of blue crabs in the ACE Basin NERR. Black lines are positive correlations and red lines are negative correlations. Solid lines are those correlations with $p < 0.05$.

In this project, I used our knowledge of the relationships between freshwater discharge and crab life history to develop a forecast model to predict the consequences of current and future drought conditions on commercial crab landings and economic value of blue crabs. The current model is a spatially-explicit, individual-based population model (IBM) that tracks blue crabs from settlement to death as they utilize different habitats within the salt marsh ecosystem (Childress 2010). I used historical and forecasted river discharge data as input to the SCBCRABS IBM to forecast historical and future blue crab landings. The results of the forecast model were shared with fishermen, marine scientists, and fisheries managers via the SC Blue Crab Forecast Webpage. Our goal is to increase awareness of the role of climate change in the health of our coastal ecosystems and to generate new hypotheses regarding the factors that limit blue crabs.

Objectives

- To parameterize an individual-based population model of South Carolina blue crabs using empirical data from the ACE Basin NERR (completed December 2013)
- To link this IBM with real-time freshwater discharge data from the USGS to forecast future abundance, landings and economic value of blue crabs.
- To distribute this forecast to fishermen, marine scientists and fisheries managers via web resources and social media.

Methods

Objective 1 – Model Building

With support from SC Sea Grant and SC Department of Natural Resources, we developed an individual-based population model known as SCBCRABS (South Carolina Blue Crab Regional Abundance Simulation – Childress 2010). The original SCBCRABS model (version 10.0) modeled a 20 mile stretch of the Ashley River, SC. The current SCBCRABS model (version 18.0) models a 35 mile stretch of the ACE Basin National Estuarine Research Reserve including the Ashepoo, Combahee and S. Edisto Rivers, SC. The spatial

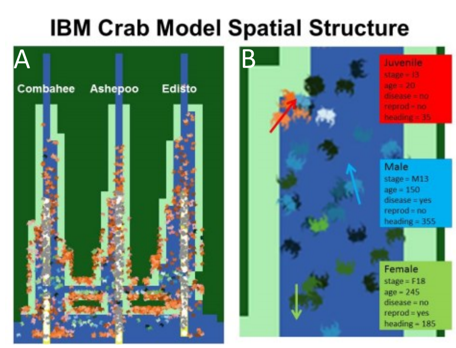

Figure 3. (A) The spatial habitat of the SCBCRABS model representing the Combahee, Ashepoo and S. Edisto Rivers in the ACE Basin NERR. (B) Individual crabs occupy different habitat patches according to movement routines that take into account season, stage, sex and salinity.

map has 1189 habitat cells of three different types; open water, shallow marsh, and land (Figure 3A). Each habitat cell also has a depth category of <1 m, 1 m, 2 m, 5 m, >5 m. These three factors, the type of habitat cell, depth, and position in the map, influence the water quality parameters present at that spatial location.

Crabs enter the model as first stage juveniles having just metamorphosed from the megalopae stage. The number that settle during any week are determined by equations that control the reproductive output of adult female crabs as well as immigration of megalopae from a source outside of the model. Settlement is spatially constrained to the lower reaches of the model in marsh habitat cells and is temporally constrained to occur during the peak period of August, September and October. Crabs grow by changing to the next largest size class in the model. There are a total of 20 size classes corresponding to a 1 cm increase in carapace width. Newly settled juveniles (J1) are assumed to be 1 cm CW while the largest adults (M20) are assumed to be 20 cm CW. Each individual crab has a sex (male or female), an age (number of days since previous molt), a disease status (no, yes), a reproductive status (no, yes), and a current heading (degrees) (Figure 3B).

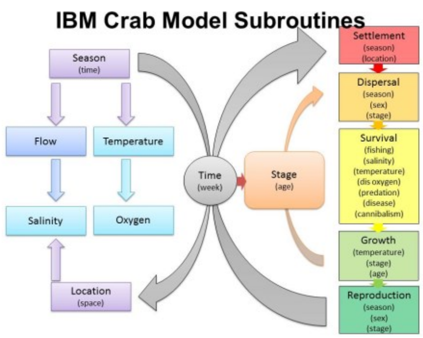

Figure 4. Flow diagram of the relationship water quality variables and crab life history subrountines.

Water quality parameters are determined for each habitat patch in the model based on a weekly time step (Figure 4). Discharge (log cubic feet / sec) is determined by week of the year and follows a sine curve based on the monthly averages from the USGS gage station at Givhans, SC (02175000). Temperature is determined by week of the year and follows a sine curve based on historical records from the St. Pierre Creek automated data station in the ACE Basin NERR. Dissolved oxygen is based on a temperature-correlated sine curve. Salinity is based on a logistic curve empirically determined by sequential sampling in the S. Edisto River using a YSI multi-probe from St. Helena Sound to the northern border of the ACE Basin NERR. The point of inflection of this logistic curve is modeled as a function of river discharge. A comparison of the model's predicted and observed salinities for any given rate of discharge are within +/- 2.0 psu at the marsh midpoint.

Each individual crab is subjected to a series of subroutines once a week that determine its dispersal (distance and direction moved), survival (including mortality due to fishing, water quality parameters, predation, disease, and cannibalism), growth (probability of becoming the next largest size class) and reproduction (number of offspring produced that return as megalopae). Of these subroutines, only growth and reproduction are currently linked to water quality (temperature), but the first objective of this project is to link salinity to the settlement, dispersal, fishing mortality, predation, and disease routines as predicted by the relationships we have observed in our four-year field study in the ACE Basin NERR (see Figure 2).

PROJECT REULTS

Objective 2 – Forecasting

To forecast blue crab landings, we first modeled future river discharge. We used the 74 year historical record (1940-2013) of river discharge for the Edisto River – Givhans Ferry, SC gaging station (USGS 02175000). Discharge levels (cubit feet / second) were common log transformed and then analyzed using an autoregressive integrated moving average (ARIMA) with a seasonal exponential smoothing function and 12 return period. ARIMA model forecasts for future river discharge were within the historical range of river discharge levels with critical minimums at or slightly below the record low flow of 2002 (Figure 5). The historical and forecasted annual discharge levels for the time period of 1990 to 2040 were then used as input to the SCBCRABS individual based model.

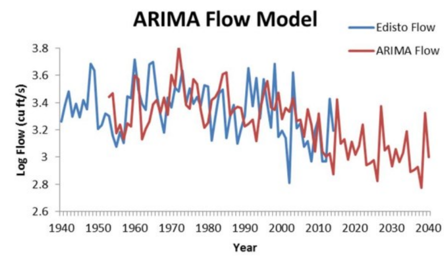

Figure 5. Observed discharge for Edisto River and predicted discharge from a seasonal exponential smoothing ARIMA forecast model.

To calibrate the IBM model landings to the SC commercial landings, model output from the time period of 1990-2013 were compared to the observed commercial landings for that same time period. Numbers of crabs landed in the model were then scaled to annual statewide commercial landings by a scaling factor of model crabs X 20,000. The median number of crabs landed in the model was 4.9 million lbs. / year, slightly below the observed landings of 5.3 million lbs. / year.

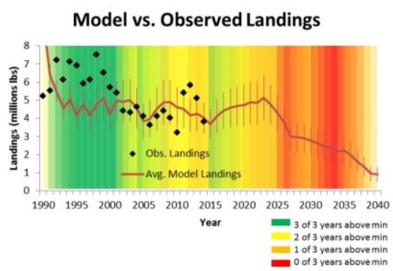

Figure 6. Comparison of SCBCRABS model landings (red line) to observed statewide landings (black diamonds). The colored heat map background is the integrated status of river discharge. Green indicates 0 of 3 previous years below the critical minimum flow and red indicates 3 of 3 previous years below the critical minimum flow.

The SCBCRABS forecast of crab landings were below the actual observed landings for the period of 1990-1999, but from the period of 2000-2013, observed landings were typically within on SD of the forecasted landings (Figure 6). The model predicted two years of decreasing landings for 2014 and 2015 followed by a steady gain in landings for the period of 2016-2023 up to 5.0 million pounds (gain in value of 1.8 million dollars annually). Beginning in the mid 2020's, landings were forecasted to decrease at a rate of 0.25 million pounds per year without recovery for the remaining period of model (until 2040). A closer examination of the forecasted landings indicated a critical minimum annual river discharge of 1250 cf/s. When this critical level is reached once during a three year period, crab landings stop increasing and remained steady. When this critical level is reached twice during a three year period, crab landings decrease. And when this critical level is reached thrice during a three year period, crab landings decline severely. These effects of perturbation persist for up to five years before the population returns to normal conditions.

Objective 3 – Dissemination

The SC Blue Crab Forecast Website was created and can be found at http://scbcrabs.blogspot.com. The web site includes additional pages of information for a lay audience (see Appendices I-IV) and a recorded presentation of the model and blue crab forecast. The SC Blue Crab Forecast Website will continue to be updated quarterly as new information is integrated into the SCBCRABS model and fisheries landings data become available for comparison with predicted landings.

Information is now being disseminated via a Facebook Group – SC Blue Crab Forecast at: https://www.facebook.com/groups/957395250994282/ where stakeholders are directed to relevant postings on the SC Blue Crabs Web Page and other articles of interest on blue crabs in general. Results of this modeling effort were presented at 2 national, 4 regional, 2 university and 3 webinars (Table 1). One published abstract has appeared to date (Childress 2014 – Appendix V) and two manuscripts are currently in preparation for submission to peer-reviewed journals.

Table 1. Presentations of work completed for this project with identification of conference, location and stakeholders present.

Date	Conference, Location	Presentation Title	Stakeholders
October 2013	VCAPS Workshop SC SeaGrant Beaufort, SC	South Carolina Blue Crab Regional Abundance Biotic Simulation	SC SeaGrant, SC DNR Blue crab fishermen
January 2014	USGS Real Time Salinity Index Workshop Charleston, SC	Forecasting blue crab distributions using an individual-based population model	USGS, CISA, SC SeaGrant, SC DNR, NOAA, NIDIS
March 2014	Benthic Ecology Meeting Jacksonville, FL	Dying of thirst: Forecasting the impact of drought on blue crabs	Universities throughout the Southeastern US
April 2014	Crustacean Resources Workshop – SCDNR Charleston, SC	Forecasting the impact of climate change on SC blue crabs	SC DNR, SC SeaGrant, USC, CofC, Blue crab fishermen
September 2014	University of South Carolina Departmental Seminar Columbia, SC	Going with the flow: forecasting the impact of climate change on South Carolina blue crabs	USC, CISA, SC SeaGrant
October 2014	SC Water Resources Conference Columbia, SC	Going with the flow: forecasting the impact of climate change on South Carolina blue crabs	SC SeaGrant, USGS, CISA, Clemson, USC, CofC, SC DNR, SC DHEC, water resource managers
January 2015	Western Carolina University Departmental Seminar Cullowhee, NC	Going with the flow: forecasting the impact of climate change on South Carolina blue crabs	WCU
June 2015	Blue crab workgroup SC Seagrant Webinar	South Carolina blue crab forecast	CofC, SC DNR, SC SeaGrant
June 2015	CISA monthly team meeting Webinar	South Carolina blue crab forecast	CISA, USC, USGS
July 2015	NIDIS DEWS team meeting Webinar	South Carolina blue crab forecast	NIDIS, CISA, USGS, Carolina DEWS, ACF DEWS
August 2015	American Fisheries Society Meeting – Crustacean Fisheries Symposium – Invited Portland, OR	Integrating field data, individual-based models and climate forecasts to predict blue crab landings	University researchers, federal fisheries scientists, state fisheries scientists, graduate students

PROJECT CONCLUSIONS

Blue crabs are one of the most important commercial fisheries in the Southeastern US and are also one of the most vulnerable to the effects of climate change. Their ability to utilize the entire estuary from the open ocean to freshwater rivers makes them vulnerable to severe fluctuations in freshwater input. Blue crabs have fastest growth and highest survival at intermediate salinities and therefore are subject to negative effects if river discharge falls below critical levels. My efforts to understand the relationship between river discharge and blue crab landings in the ACE Basin NERR in South Carolina suggest that blue crab landings vary with freshwater discharge. When Edisto River annual flows exceed 1250 cf/s for three or more years in a row, blue crab landings will increase. But as river flows fall below this critical minimum flow, landings will level off or decrease depending on the frequency in which this critical level is observed. Using a simple statistical approach to forecasting future river discharge, the landings for blue crabs in SC is expected to rise modestly until 2023 and then decrease thereafter. The downturn was predicted to correspond with the next severe drought and is unlikely to recover given the downward trajectory of future river discharge levels. This negative impact is most likely to impact low flow rivers (such as the Combahee River) first, while high flow rivers may actually see increased landings in the near future (such as the Edisto River). This may mean that stakeholders will need to move their fishing efforts to higher flow rivers as river discharge decreases under future climate scenarios. The certainty of the proposed downturn in the fishery should not be considered an exact, single point in time. These models are based on an average of hundreds of model runs and represent a broad distribution of potential outcomes (Figure 7). However, the models are robust in the overall conclusion that eventually, freshwater decreases will begin to have a negative impact on crab landings.

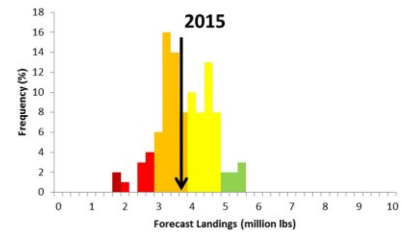

Figure 7. Distribution of forecasted landings for the year 2015 compared to the observed landings for 2014 (black arrow). The stochastic nature of the relationship between salinity and crab life history allows for a wide range of possible outcomes given the same freshwater input to the model. However, all models forecast a decrease in fisheries landings if freshwater discharge continues to decrease.

FUTURE DIRECTIONS

Now that we have a working model for forecasting blue crab landings, future efforts should focus on three new objectives: (1) incorporating more realistic models of future river discharge from downscaled regional climate forecasts, (2) expanding the latitudinal coverage of the blue crab forecast by comparing river discharge and commercial landings across the entire SE and Gulf coasts, and (3) educating stakeholders about the resources available on the SC Blue Crab Forecast Webpage.

Objective 1 has been initiated and is in collaboration with Greg Carbone and Dan Tufford (CISA & USC). They have been using the OpenNSPECT forecast tool coupled with downscaled precipitation forecasts for different IPCC scenarios to provide a range of potential base flow forecasts for the Edisto River basin. I will then use these new river forecasts as inputs into the SCBCRABS IBM and generate a new range of blue crab forecasts, one for each of the different IPCC climate change scenarios.

Objective 2 would focus on utilizing the new coastal drought index (CDI) developed by Paul Conrads (USGS) as a standard measure for estimating the critical minimum flows needed to sustain blue crab population growth. We would start by calculating the CDI for the Edisto River from salinity data record of the ACE Basin NERR water quality station. Then we would determine the appropriate integration of CDI scores to observed commercial crab landings to identify the critical thresholds of crab response. We would then apply these same criteria to CDI scores for rivers and fisheries in Texas, Louisiana, Florida, Georgia, North Carolina, Virginia and Maryland. Funding from NIDIS – DEWS would be essential to complete this objectives and would benefit both the Carolinas and ACF DEWS programs.

Objective 3: The SC Blue Crab Forecast Website and Facebook Group will continue to be updated quarterly with the latest forecasts for blue crabs and the evaluation of potential risks due to immediate river flow conditions. Future revisions include (1) an expanded economic forecast for the fishery given different climate scenarios, (2) a hands-on web based version of the SCBCRABS IBM that stakeholders can use to conduct their own scenarios of the impacts of climate change on blue crab landings, and (3) a map based river forecast for optimal blue crab fishing based in real-time freshwater flow data. Again the ability to provide all of these new products and to maintain the quarterly updates of the SC Blue Crab Forecast Webpage will require a modest amount of financial support.

NIDIS FEEDBACK

It has been a great pleasure to have an opportunity to be involved with the Carolinas Integrated Sciences and Assessments team. It has allowed me to develop new collaborations (Tufford – USC, Carbone – USC, Conrads – USGS) and enhance ongoing collaborations (Fowler – SC DNR, Davis – SeaGrant). I am also looking forward to expanding my interactions with new collaborators at the ACF DEWS project. My only suggestion for an area for improvement would be to clarify instructions for how one would submit a proposal for future funding considerations. I would very much like to consider for future funding opportunities, but am still uncertain how to initiate this process.

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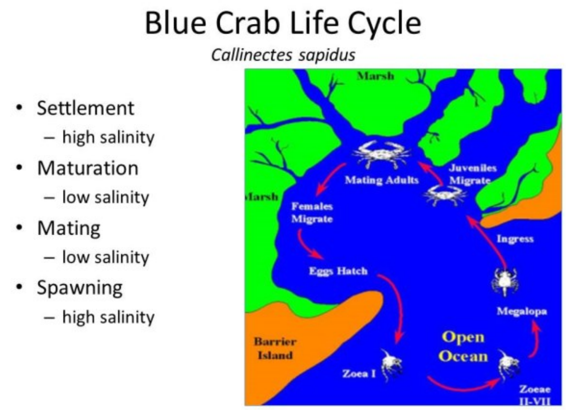
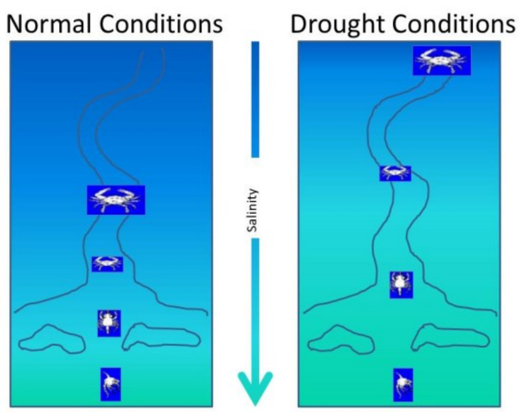
APPENDIX I: Blue Crab Life History



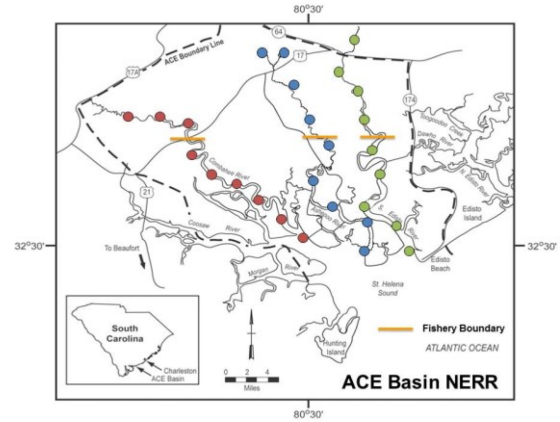
Blue crabs live in estuaries where freshwater rivers meet the saltwater ocean. Crabs occupy both saltwater habitats and freshwater habitats at different parts in their life cycle. Females carry their eggs to offshore locations to release their larvae into the open ocean. These larvae (zoea) develop for approximately 30 days in nearshore coastal waters before coming back in shore. The last zoea stage molts into a postlarvae (megalopae) which is the life stage that rides the tides into the estuary and settles into shallow seagrass or marsh grass habitats. The megalopae molts into a first stage juvenile crab. Juvenile crabs slowly move upriver into the freshwater rivers over the next 18 months growing larger and moving further inland. When they reach sexual maturity, females release a pheromone to attract a male for mating. Mating usually begins in the early spring and may continue until the fall. Once females are mated, they will begin their downriver migration back to the open ocean to complete their life cycle.



Crabs know how far to migrate upriver by the salinity of the water. During drought years when less freshwater is flowing into the estuary, the salinity from the open ocean extends further upriver. This increases the distances that crabs must migrate to complete their life cycle. This increased distance of travel has several potential negative consequences to crabs. First, juvenile crabs grow faster at intermediate salinities (20-25 psu or practical salinity units). During drought years it takes longer for juveniles to reach this range of optimal growth. Second, crabs encounter a parasite (Hematodinium spp.) only in high salinity water. So droughts increase exposure and mortality due to disease. Third, females expend a lot of energy migrating upriver to find males and then again downriver to release larvae. This extra energy could be used to make more eggs in years when drought conditions are not present. Finally, females use salinity cues to know when they have returned to the open ocean for the release of their larvae. If females encounter full seawater (35 psu) before they leave the mouth of the river, the larva may not make it off-shore to complete their life cycle.

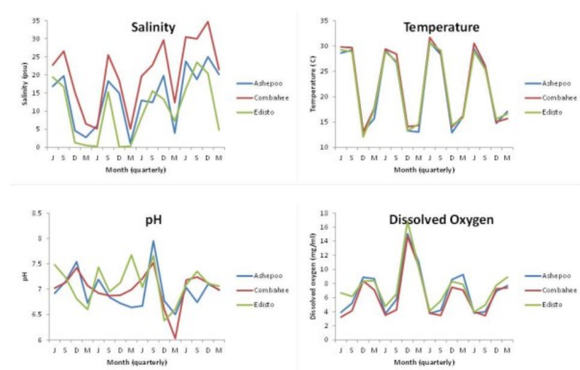
APPENDIX II: Field Study of Salinity Impact on Blue Crabs

To determine the role that salinity plays on blue crab settlement, growth and survival we conducted a series of field surveys and experiments in the ACE Basin National Estuarine Research Reserve. This study was funded by Clemson University and the SC SeaGrant program and ran from March 2008 to March 2012. To monitor the response of blue crabs to changing salinity conditions, we sampled crabs at nine stations (1 being closest to St Helena Sound and 9 being closest to the northern ACE Basin boundary) in each of the three rivers (from left to right, Combahee, Ashepoo, and Edisto). These three rivers differed in the amount of freshwater discharge and thus, had different salinity profiles. We sampled these four rivers quarterly (March, June, September, December).



In order to measure water quality, we used a YSI multiprobe to measure temperature, salinity, dissolved oxygen and pH at each sampling station. We also counted crab pot buoys between each water quality station to estimate fishing effort. In order to measure crab abundance at each sample station, we placed four modified commercial crab pots (wrapped in mesh to retain juvenile crabs) at each station in the river and pulled them after a 4 hour soak. All crabs were returned to the field station for further processing. Every crab was sexed, weighed and measured to the nearest 0.1 mm across the width of the carapace (CW) from the tip of one lateral spine to the tip of the other lateral spine. Each crab was photographed and had a blood sample drawn and preserved for analysis of Hematodinium spp. infection. All crabs were then released unharmed back into the estuary.

These graphs show how water quality measures changed between seasons and years at the mid-point on the river (station 5). The x-axis are the 16 sampling dates beginning in June 2008 through March 2010. All four water quality measures differ by season with salinity and temperature showing peaks in June or September and dissolved oxygen showing peaks in December or March. Temperature and dissolved oxygen did not differ between the three rivers but salinity and pH did. The Combahee River had the highest salinity profiles and showed an increase in salinity from 2008 to 2012.



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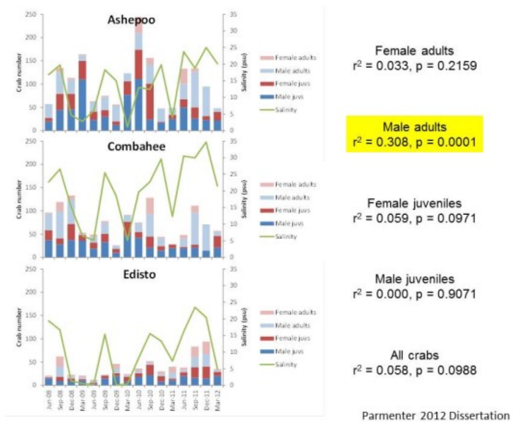
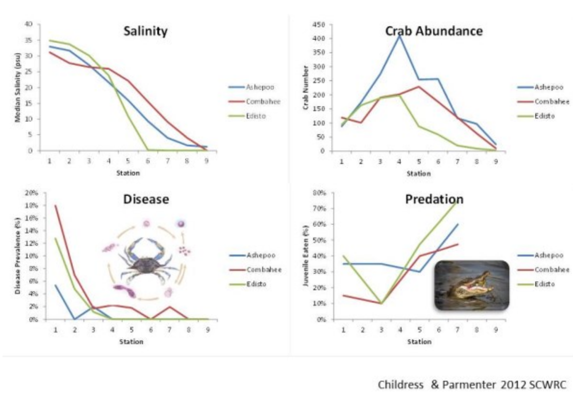


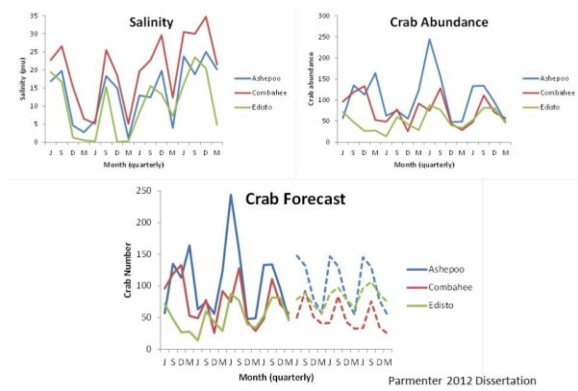
These graphs show the sum of blue crabs (all nine stations combined) by sex and size for all 16 sampling dates within each of the three rivers. Blue bars are males and red bars are females. Darker bars are juveniles and lighter bars are adults. The green line overlaying the graph is the salinity at the mid-point of the river (station 5). Clearly blue crabs are most abundant in the intermediate salinity Ashepoo River and least abundant in the low salinity Edisto River. There was no strong pattern of seasonal blue crab abundance with seasonal variation in salinity. Adult males were the only subclass of blue crabs whose abundance was correlated with salinity as more adult males were observed on low salinity sample dates.

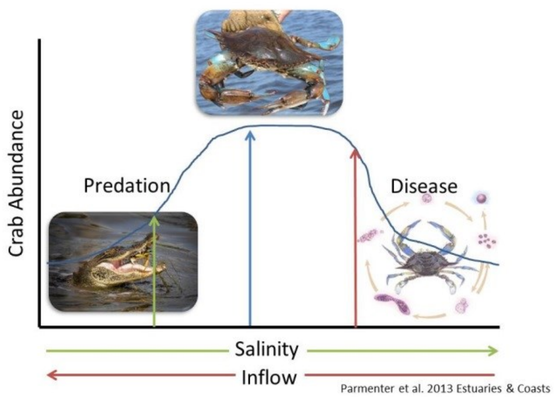
In order to test the hypothesis that changes in salinity influence crab populations, we conducted one manipulative field experiment and three observational studies. To estimate the impact of salinity on predation of juvenile crabs, we tethered 20 juvenile crabs to a weighted line and placed them at four stations (1, 3, 5, 7) in each of the three rivers. To estimate the impact of salinity on disease, we used a PCR-based laboratory assay to identify which of the crabs surveyed were infected by Hematodinium spp. To estimate the impact of salinity on fishing effort, we compared the number of crab pots being fished to the salinity of each region of the three rivers. And finally to estimate the impact of salinity on blue crab larval settlement, we deployed and sampled larval collectors at four stations (1, 2, 3, 4) in each of the three rivers.



We found a significant negative relationship between salinity and relative predation. Juvenile blue crabs are eaten more frequently in low salinity stations and in the low salinity river. We found the opposite pattern with regards to disease. Crabs at high salinity stations and in the high salinity river had much higher levels of Hematodinium spp. infection. Neither fishing effort nor larval settlement showed any consistent patterns in relation to changes in salinity. Given that high salinity increases disease and low salinity increases predation, it is not surprising that blue crab abundance is highest at stations with intermediate salinity and in the river with intermediate salinity.

Given that crab abundance may be harmed by salinities that are either too low or too high, what is the consequence of droughts on blue crabs? During this four year study freshwater input to the ACE Basin hit historical lows in 2008, 2011 and 2012. As a result, the average salinities slowly increased throughout the study in all three rivers. Surprisingly, this caused a different response to crab numbers in each of the three rivers. In the low flow Combahee River, increasing salinity caused decreasing crab numbers likely due to increasing disease. In the high flow Edisto River, increasing salinity caused increasing crab numbers likely due to decreasing predation. But in the intermediate flow Ashepoo River, increasing salinity had little effect because salinities remained in the optimum range for blue crabs.

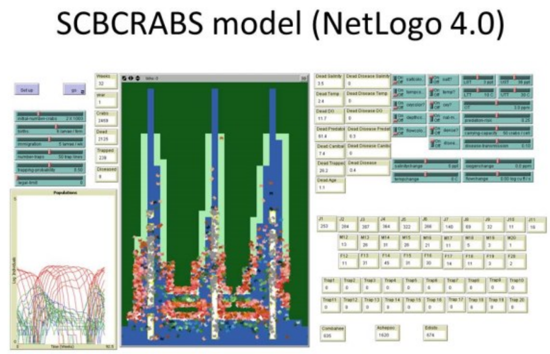


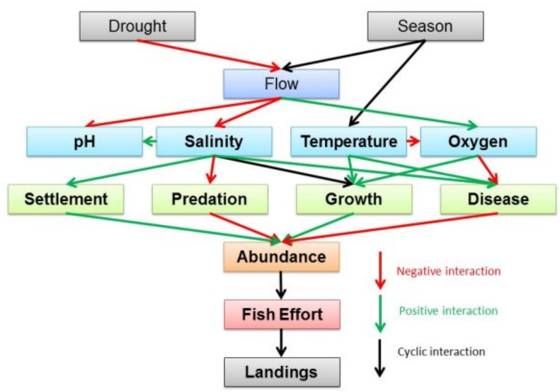


This figure summarizes the findings of our four year study of the impact of salinity on blue crabs. Crabs do best at intermediate flow levels and intermediate salinity locations. When flow is decreased like during a drought, salinity increases and the impact can be negative through an increase in disease. This is likely to occur more in the lowest flow locations. However, during a drought the increase in salinity may also be positive by reducing predation. This is likely to occur only in the highest flow locations. The future of blue crab will depend on flows remaining in the optimal range to produce the largest salinity sweet spot across the greatest number of rivers.

APPENDIX III: SCBCRABS Individual Based Model (IBM)

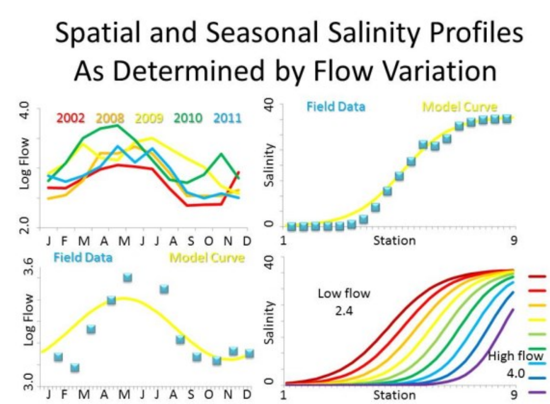
The SCBCRABS individual based model is a computer program that tracks a population of blue crabs moving about a simulated habitat. The program was written using the modeling platform NetLogo 4.0.5. This program allows the user to define characteristics of each habitat patch and each agent (individual blue crab) and keep track of what happens to every individual in the model. The results of a simulation run provides data on the population structure of blue crabs in response to environmental conditions that we wish to study, such as drought.

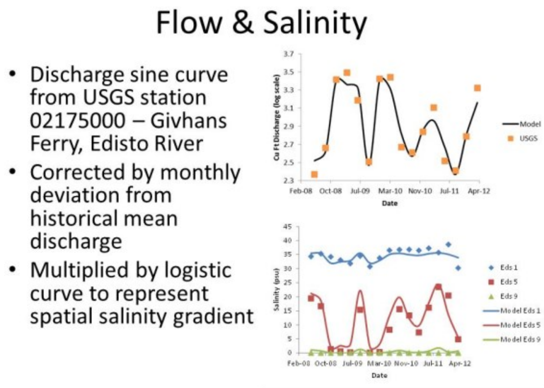




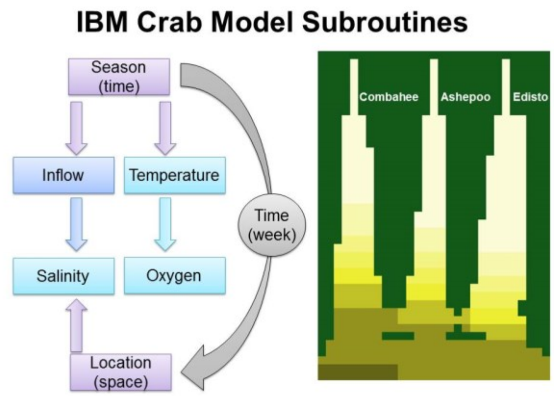
All individual based models (IBMs) make use of known relationships (equations) between environmental factors and agents (individual blue crabs) that occur in the model. The key to a realistic individual based model is how well you can accurately describe these relationships. Consider this simplified diagram of a subset of factors that might influence the relationship between drought and commercial blue crab landings. Some of these relations will be positive (green arrows) while others will be negative (red arrows). Still other relationships will be cyclical or non-linear (black arrows). Single factors such as salinity may have many different pathways to influence crab abundance. A simple equation is unlikely to explain much variation in this relationship. Furthermore, this relationship is likely to change through time and space. So the value of the IBM approach to studying the effects of drought on crab abundance, it that it takes into consideration many different and often opposing relationships to produce a more realistic outcome.

The best way to describe these relationships of interest is to actually measure them in the field. During our four-year study of blue crabs in the ACE Basin NERR, we took lots of measures of environmental data, so we could construct better equations for the SCBCRABS model. For example, using data from the USGS gaging station at Givhans Ferry, SC (02175000) we were able to relate Edisto River Flow rates to season and construct a sine-curve equation that captures the change in average river flow by season. We also empirically measured salinity in response to spatial position in the estuary from the mouth of the river (station 1) to the northern boundary of the ACE Basin NERR (station 9). We then fit a logistic curve to these empirical observations so the model could predict realistic salinity levels at any location in model given the season and the current river flow.

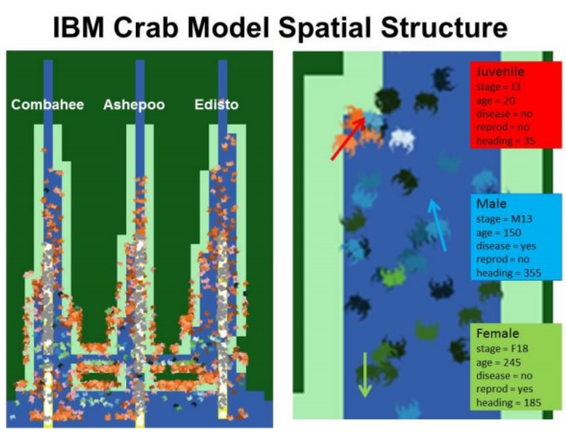




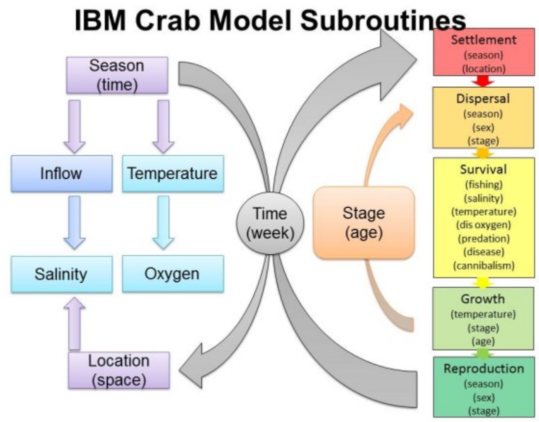
Before running simulations using these complex equations, we evaluated how well our relationships compared to our field observations to see how well our model could match actual observations of salinity in the field. Our modeled salinities did an excellent job tracking the spatial, seasonal and annual variation in salinity actually measured during our four year field study.



The IBM is spatially-explicit which means each habitat patch in the model is given specific characteristics which can then influence the agents (individual blue crabs) in the model. This is accomplished by defining patch conditions in the set-up routine and updating patch conditions at each time step of the model. In the example above, the shades of yellow shown in the depiction of the habitat cells of the model represent a gradient of salinity from 35 psu salinity (brown) to 0 psu salinity (light yellow). You can also see that the salinity profile is slightly off-set for each of three simulated rivers in the model matching the observed difference in flow between the Combahee, Ashepoo and Edisto Rivers. The model keeps track of time on a weekly time step and thus the model knows which week during the annual cycle it is currently at. This allows to model to make use of that sine-curve of flow presented above to accurate influence the seasonal salinity profile for each habitat cell in the model. Similar relationships update each patch for temperature, dissolved oxygen and pH.

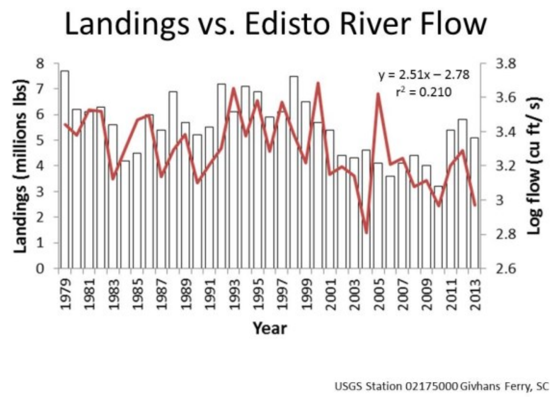


The next step is to add agents (individual blue crabs) to the model and let them move around the available habitat cells. In this model we only keep track of blue crabs once they have settled into the marsh and molted into their first benthic juvenile. Newly settled juvenile crabs (J1) are crabs with a 1 cm carapace width (CW). As they grow during the course of their life time they will molt to the next largest stage (J2, J3, J4...) increase in size in 1 cm CW increments. Juvenile in the model are red with darker shades representing older individuals. When crabs reach sexual maturity (stage 13) crabs become either M13 mature males (blue) or F13 mature females (green). They are not capable of participating in the reproductive part of the model subroutines. Movement of each crab stage assumes that they will move toward their preferred salinity. This was estimated from empirical observations of crab size and location from the four-year field study in the ACE Basin NERR. Since the salinity of habitat cells is constantly changing, the crabs in the model migrate upriver and downriver in a seasonal cycle similar to the seasonal migrations observed in the field. It is this movement of crabs that bring them into contact with commercial fishing pots, represented in the model as a long row of yellow habitat cells with white circles in them. When a crab encounters a crab pot, there is a chance that the crab will enter the pot and get caught (grey crabs). This allows us to fish for our model crabs in a fashion similar to how fishermen fish for crabs in the ACE Basin. The range and densities of crab pots in the model were derived from observed fishing effort seen during the four-year field study in the ACE Basin.



Finally, the model includes a series of subroutines that follow the steps an individual crab must go through during its lifetime. For example the first model subroutine adds new recruits (J1s) to the model based on the reproductive output of females from the previous turn of the model. Then the model allows each individual crab to move (Dispersal), avoid being killed (Survival), grow (Growth) and if ready, reproduce (Reproduction). The probability of accomplishing these challenges depends on the individual's stage, sex, age, disease condition as well as the patch conditions (temperature, salinity, dissolved oxygen, disease abundance, predator abundance). After every crab has been through these four subrountines, the model enters the next time step (one week interval), the patches are all updated, and the individual crabs go through the subroutines again. Once a crab is killed or caught in a crab trap, it is forever removed from the model. The relationships (equations) that link patch conditions such as salinity to crab effects such as predation or disease were estimated from empirical observations collected during the four-year field study in the ACE Basin NERR. Thus the model allow us to scale up many different effects that salinity has on individual crabs in a realistic fashion given that crabs are constantly on the move and salinity is constantly changing.

APPENDIX IV: Forecasting Future Crab Landings

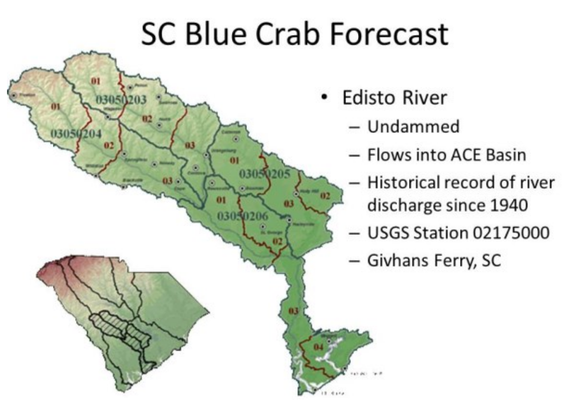


One of the first observations we made that began our investigation of freshwater flow and blue crab landings was that years of rapidly decreasing freshwater discharge were correlated with years of rapidly declining commercial crab landings. This correlation had the highest predictive power when flow from two years prior was used to predict the current year's crab landings (shown above). This gives us an immediate back-of-the-envelope approximation for future blue crab landings by knowing the annual flow of the Edisto River two years earlier. This relationship can be described by this simple linear equation:

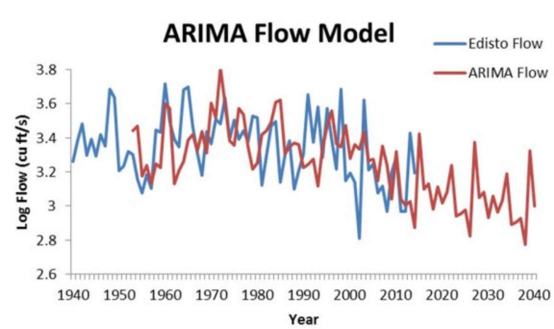
Expected landings (in millions lbs) = 2.51 X log (Edisto annual flow in cu ft/s) - 2.78 (a constant)

So given that the Edisto annual flow for 2013 was 931 (cu ft/s) then the expect blue crab landings for 2015 should be:

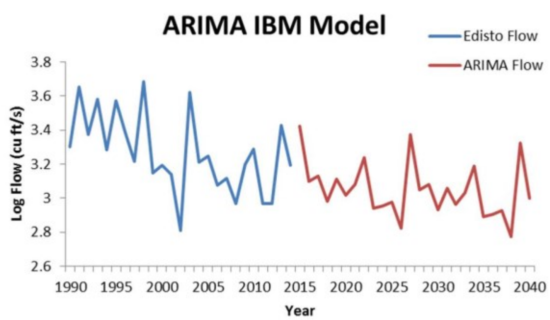
2.51 X log(931) - 2.78 = **4.67 million lbs.**



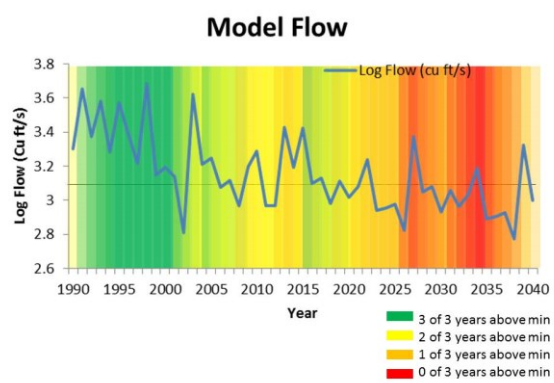
So why choose the Edisto River freshwater discharge levels rather than some more integrated measuring involving all of the rivers in South Carolina? First of all, SC river discharges are highly correlated with adjacent rivers such that one is likely to represent the trend of the whole set. Second, the Edisto River is undammed and thus, shows normal seasonal cycles unimpacted by regulation for hydroelectricity production. Third, the USGS gaging station at Givhans Ferry, SC (02175000) has one of the longest historical record of discharge records dating back to 1940. Finally, the Edisto River was river used to parameterize the SCBCRABS IBM with the ACE Basin NERR field study.



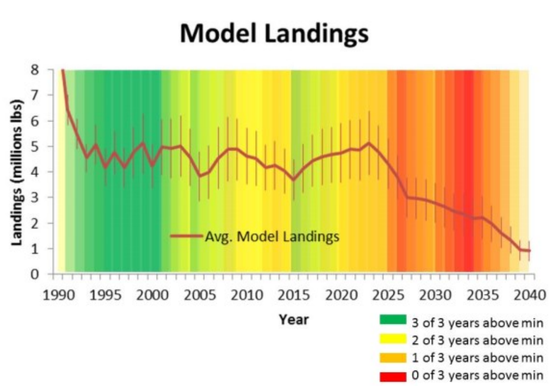
This graph shows the historical record of Edisto River discharge (at USGS station 02175000) over the last 75 years (blue line). At first glance it is easy to see that discharge levels vary a lot from year to year and that recent discharge levels are below the levels they were prior to 1990. So if we want make a best guess what the river discharge levels will be in the future, we should consider both the slope of this decline in discharge levels and the periodicity of the interannual variation. One mechanism to do this is to use an auto-regressive integrative moving average model (ARIMA). This model assumes a sine-curve smoothing function with a period of twelve years. I chose this period for it was the best period for a simple sine-curve function fit to the historical record and it also approximates the periodicity of larger global weather patterns that affect precipitation (ENSO, NAO). The ARIMA model is fit to the historical record (red line) and then projected forward in time based on the predicted future flow levels. Overall the slope of the flow decline is approximately 0.04 which is less than the rate of decline observed over the last 10 years. Likewise the magnitude of the forecasted droughts (2026 and 2038) are of similar magnitude to the one observed in 2002.



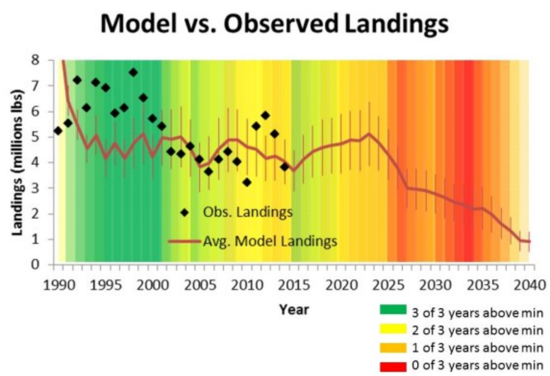
To merge this ARIMA model of Edisto River flow with the SCBCRABS blue crab model, I chose to focus the simulation runs over a 50 year period from 1990 to 2040. That means for the first 25 years of the model run, the flow input is the actual historical data of monthly river discharge from the Givhans Ferry USGS gage (blue line). For the years from 2015-2040, the river flow is assumed to follow the predictions from the ARIMA flow model (red line). Data for weekly flow levels were then read into the SCBCRABS model as an input file with 2600 time steps (52 weeks X 50 years).



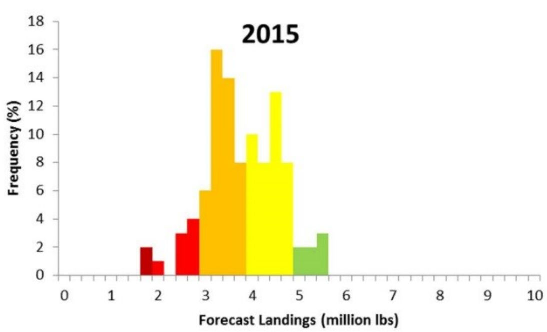
To better visualize the cumulative impact of freshwater flow has over blue crab for multiple years, I constructed a heat map that captures the impact of droughts multiple years after the event. I first selected a critical minimum annual flow level based on the annual flow level that seemed to have the greatest influence of future crab landings. The critical minimum flow was 1250 cu ft/s flow (log 3.1). In this heat map, each year is color coded by the number of years prior where the flow was above the critical minimum level. For example, year 2000 is green because flow for 1998, 1999 and 2000 were all above the critical minimum flow whereas 2012 is orange because only flow for 2010 but not 2011 or 2012 was above the critical minimum flow. The impact of these hydrological drought events (annual levels below the critical min of 1250 cu ft/s) is presumed to impact blue crabs for a five year period and thus the green color assigned to 2000 extends through 2004 and the orange color for 2012 extends through 2016. Thus, crabs should do well during the green years and should not do well during the red years.



Here we show the estimated annual commercial landings from the SCBCRABS ARIMA IBM. The model output of crabs trapped were divided by a constant (50) to derive the approximation of the annual landings in millions of lbs. The line connects the mean landings for 100 runs of the model and the error bars represent +/- 1 standard deviation. The model predicts relatively high or increasing blue crab landings for periods of good water flow (green years). When an isolated drought occurs (yellow years), crab landings usually remain stable without strong increases or decreases. When droughts occur twice during a three year period (orange years), crab landings usually decline. When severe, prolonged drought occur (red years), crab landing decrease more rapidly and are less responsive to recovery when higher flows return. The forecast for the period of 2015 through 2023 suggests a gradual increase in landings as river flows continue to be above the critical minimum flow. However, the landings are expected to decrease with the arrival of next prolonged drought beginning in 2023. By then river flows are expected to regularly be below the critical minimum flow, a condition where a sustainable blue crab population would be unlikely.



So is there anyway to test the validity of the model forecast? We can compare how the model performed relative to the observed SC annual landings for blue crabs (black diamonds). If the model is accurately predicting crab landings, the observed landings should fall within the range of values shown by the vertical error bars 67% of the time. During the first ten years (1990-1999) the observed landings fell within this margin of error only 20% of the time with 80% of observed landings coming in higher than predicted. This suggest that the model may be to harsh on crabs in elevated flow conditions which may not be as bad as low flow conditions. During the second ten years (2000-2009) landings fell within the margin of error 90% of the time with observed landings coming in both higher and lower than predicted. This suggests that the model may be more accurate when river flows are at or near the critical minimum flow. Finally, in the most recent five years (2010-2014) the model failed to predict an unexpected dip followed by a three year rise in commercial landings that occurred during yellow and orange river flow conditions. These results suggest that actual landings are much more variable year to year than the average of 100 runs of the model which minimizes severe changes from one year to the next.



Here is the entire range of model forecasts for 2015.

Mean forecast = 3.69
Median forecast = 3.67
67% range 2.90 - 4.48
95% range 2.11 - 5.28

Appendix V: Going with the flow: Forecasting the impact of climate change on blue crabs

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REFERENCE: *Proceedings of the 2014 South Carolina Water Resources Conference*, held October 15-16, 2014 at the Columbia Metropolitan Convention Center.

ABSTRACT. Blue crabs are one of the most important commercial fisheries in South Carolina, but landings have declined during recent droughts. Climate forecast models suggest that in the Southeastern US, we can expect our future climate to be wetter, hotter and more variable than in the past, with a net decrease in freshwater surface flow. To better understand the complex interaction of climate change on river flow and blue crab abundance, we used a spatially-explicit, individual-based population model (ACE-SCBCRABS) parameterized from field observations of water quality, crab abundance, predation, disease, and fishing effort collected in the ACE Basin National Estuarine Research Reserve. In this study, we explored how changes in river flow under future scenarios of climate change might impact blue crabs landings over the next 75 years. We examined how the rate of freshwater flow decrease and the degree of inter-annual flow variability might interact to influence crab abundance, commercial landings, and disease. Models were run for 150 years beginning with flow rates observed in 1940 and projecting forward in time to the year 2090. Decreasing freshwater flow and increasing inter-annual variability both caused a significant decrease in crab landings. Models run under 1940 conditions of flow decline and variability show crab landings at our current harvest level. Models run under 1975 conditions of flow decline and variability show a reduction in crab landings of 30%. Models run under 2010 conditions of flow decline and variability show a reduction in crab landings of 76%. These results suggest that current levels of freshwater decline and inter-annual variability there is a 29% risk of collapse for the South Carolina blue crab fishery by the year 2090.

INTRODUCTION

Blue crabs (*Callinectes sapidus*) are one of the most important commercial fisheries in the state of South Carolina with annual landings averaging 5.5 million lbs. Inter-annual variation in SC crab landings is significantly correlated with annual levels of freshwater discharge explaining > 20% of its variation (Childress 2010).

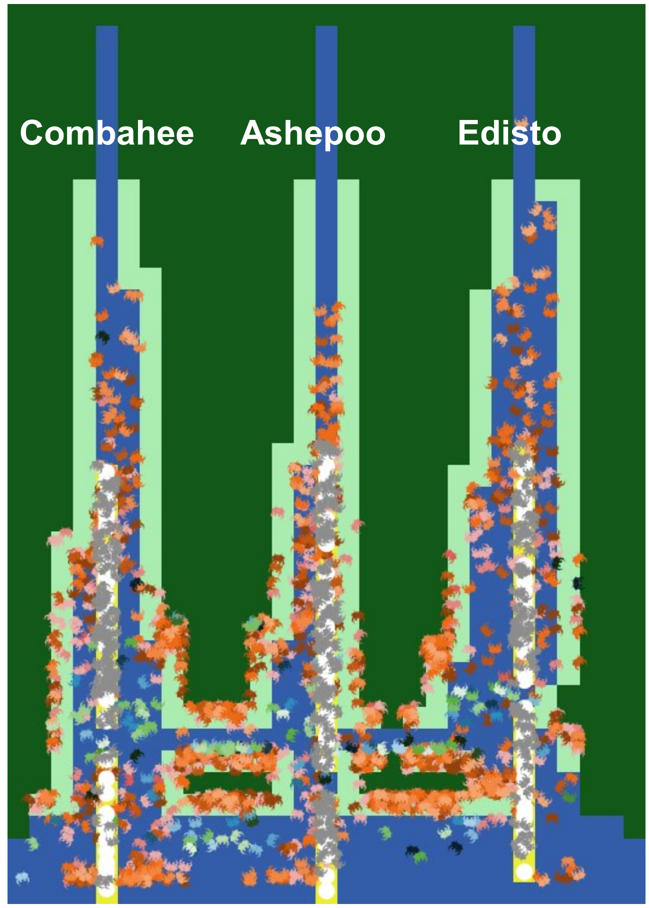

Figure 1. Visual representation of the ACE-SCBCRABS individual-based population model (IBM). Each habitat cell of the model (blue = water, light green = shallow marsh, dark green = land, white = crab trap) is parameterized for temperature, salinity, and dissolved oxygen which vary with season and freshwater flow specific to each of the three rivers, Ashepoo (middle), Combahee (left), and Edisto (right). Crabs (red = juvenile, blue = males, green = females, gray = trapped) are removed from the model by mortality from temperature, salinity, dissolved oxygen, disease, predation, cannibalism, and fishing. Crabs are added to the model by reproduction from mature females. Freshwater flow input to the model was varied to represent historical and projected changes in surface run-off.

During droughts, freshwater input to the marsh decreases and salinity increases. As salinity increases, crab abundance decreases due to increasing infection by a lethal parasite, *Hematodinium* sp. (Lee and Frisher 2004; Parmenter et al. 2013). However, the degree to which crab decline is linked to decreasing freshwater depends on the level of freshwater flow into the marsh. A four-year study of the blue crabs in the ACE Basin National Estuarine Research Reserve (NERR) during the 2010 drought found that crabs decreased in the low flow Combahee River due to increased disease but increased in the high flow Edisto River due to decreased predation by freshwater predators (Parmenter 2012).

To better understand the net impact of freshwater flow on crab population dynamics and fisheries landings, we constructed a spatially-explicit individual-based population model (IBM) for the crabs of the ACE Basin NERR (Childress and Parmenter 2012). Using this model (Figure 1), we evaluated the impact of historical, current and projected decreases in freshwater on future blue crab landings.

PROJECT DESCRIPTION

In this experiment, we asked the ACE-SCBCRABS model to project future blue crab population density and commercial landings for different scenarios of freshwater decline. Our hypothesis was that both the rate of freshwater decline and the amplitude of flow variability would negatively impact future crab abundance.

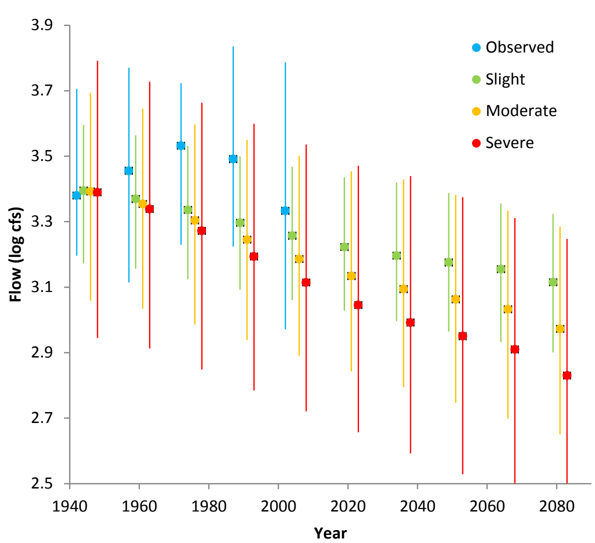

Figure 2. Freshwater flow (average, minimum and maximum) for 15 year periods from 1940 to 2090 based on the historical record of Edisto River discharge (observed). We simulated the rate of flow decline and amplitude of inter-annual variation from 1940 (slight), 1975 (moderate) and 2010 (severe) as input for 500 replicate runs of the ACE-SCBCRABS model.

METHODS

First, we modified the ACE-SCBCRABS IBM to include an annual decline in freshwater flow and increase in inter-annual variability estimated from the historical record of flow from the Edisto River (USGS gaging station 02175000). We set these levels to approximate the rate of flow decline and variability in 1940 (slight, slope = 0.002, amplitude = 0.2), 1975 (moderate, slope = 0.003, amplitude = 0.3), and 2010 (severe, slope = 0.004, amplitude = 0.4) (Figure 2). Inter-annual variability was modeled as a best fit sine curve with a period of 8 years.

Then, we ran the model 500 times with starting values of flow at 3.4 (approximately 2500 cfs) and 2000 crabs (approximately 6.6 million lbs.). We measured crab abundance and % diseased crabs annually for 150 years (1940-2090). From the model output, we projected annual SC landings (in millions lbs.) by multiplying by a scaling factor of (0.00333).

Sensitivity analysis of flow decline (slope) and inter-annual variability (amplitude) was conducted using a fully-factorial RMANOVA. Analysis of crab abundance at the simulation endpoint was conducted using a one-way ANOVA with four levels of conditions (observed, slight, moderate and severe) with Tukey's HSD post-hoc comparisons.

RESULTS

Blue crab abundance, and hence, commercial landings were sensitive to both the rate of freshwater decline (RMANOVA, $F = 3.548$, $df = 4,49$, $P = 0.0128$) and the inter-annual variation (RMANOVA, $F = 91.23$, $df = 4,49$, $P < 0.0001$). The relative importance of each changed with time with amplitude variation explaining the majority of crab abundance variation in the early years and slope variation explaining the majority of variation in the later years. Under conditions of slight flow decline and variability, crab abundance remained relatively stable for the entire simulation period (Figure 3A). With moderate flow decline and variability, crab abundance initially decreases (1940-1970) due to increased predation followed by an increase when flows are optimal (1970-2000) to a slight decline thereafter as rising salinity increases disease (Figure 3B). With severe flow decline and variability, crab abundance decreases almost the entire period with one brief period of positive growth (1990-2000). This steady decline is due to both increased predation when flows are high and increased disease when flows are low (Figure 3C).

To estimate the probable outcome of future scenarios for the SC blue crab fishery, we plotted the frequency of final crab abundance (scaled to annual landings) of 500 model runs for the endpoint year 2090.

Historical records of SC blue crab annual landings from 1979-2013 have a mean (+/- SD) of 5.50 +/- 1.14 million lbs. (Figure 4A). Simulated annual landings for 2090 assuming a slight flow decline and variability are statistically similar (5.41 +/- 1.04) (Figure 4B). However, simulated annual landings for 2090 for a moderate (Figure 4C) and severe (Figure 4D) flow decline and variability are significantly lower with means of 3.87 +/- 0.88 and 1.34 +/- 0.60 million lbs. respectively (Tukey's HSD post-hoc comparisons).

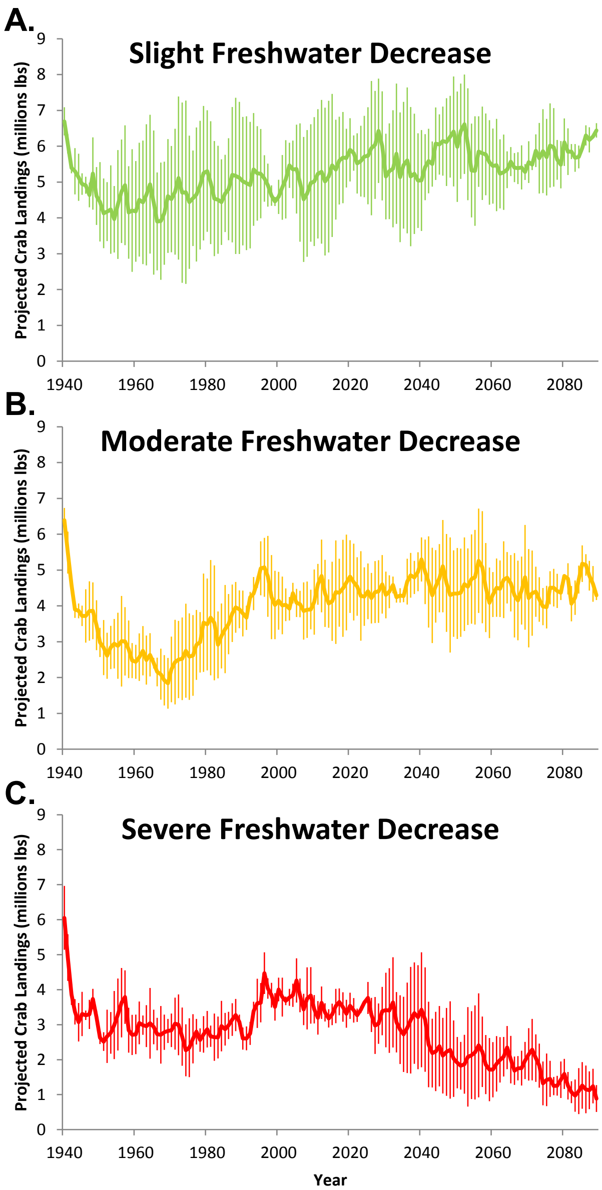

Figure 3. Projected annual landings of blue crabs (mean +/- SD) for 150 year from 1940 to 2090. We simulated the rate of flow decline and amplitude of inter-annual variation using rates from (A) 1940 (slight decrease), (B) 1975 (moderate decrease) and (C) 2010 (severe decrease) as input for 500 replicate runs of the ACE-SCBCRABS model.

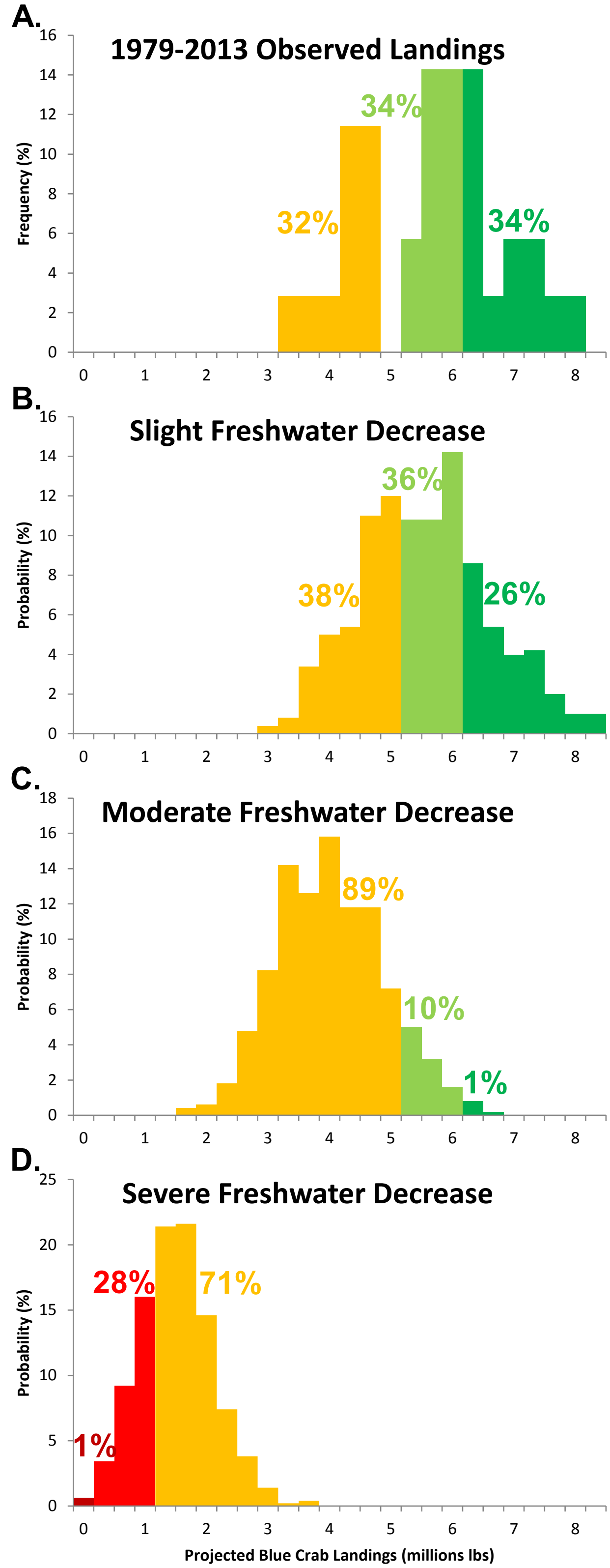

Figure 4. Frequency histogram of SC blue landings (A) observed from 1979 to 2013, (B) projected using slight flow decline and variability, (C) projected using moderate flow decline and variability, and (D) projected using severe flow decline and variability.

DISCUSSION

Blue crabs are one of the most important commercial fisheries in South Carolina, but landings have declined during recent droughts (Childress 2010). This relationship between freshwater discharge and blue crab landings has been observed for other populations of blue crabs including those in Florida (Wilber 1994), Georgia (Lee and Frischer 2004) and Louisana (Sanchez-Rubio et al. 2011). Our previous research has found that during droughts the salinity profiles in the estuary shift upriver increasing exposure to higher salinity water. Droughts cause blue crabs in high salinity rivers to decline due to increased disease while blue crabs in low salinity rivers increase due to reduced predation (Parmenter 2012; Parmenter et al. 2013).

Our modeling effort revealed that both freshwater flow decline and freshwater flow inter-annual variability significantly influenced crab abundance. When the model was run with a slight flow decline and variability, the number of crabs forecasted for 2090 was statistically similar to observed annual landings. However, when the model was run with either moderate or severe flow decline and variability, the number of crabs forecasted for 2090 significantly decreased 30% and 76% respectively.

In all scenarios, crabs initially increase as predation declines with increasing salinity, but eventually crabs decrease due to increasing disease. A similar pattern of initial increase for several decades followed by steady decline in recent years is corroborated by a recent review of blue crab population connectivity along the Atlantic coast (Colton et al. 2013). These populations also show a cyclic inter-annual variation in crab abundance similar to the patterns observed in our model populations.

How much will river flows in the Southeastern US change in the future? Climate forecast models suggest that we can expect our future climate to be wetter, hotter and more variable than in the past, with a net decrease in freshwater surface flow (Seager et al. 2009). This will have broad and significant effects throughout coastal ecosystems (Gilbert et al. 2012). Our research suggests that commercial blue crab landings will significantly decrease (landings below 5 million lbs.) with an 89% probability under a moderate flow decline and variability; and will potentially collapse (landings below 1 million lbs.) with a 29% probability under a severe flow decline and variability.

The risk of blue crab fishery collapse by the end of this century is non-trivial, but is reversible if river discharge levels can be restored to historical levels. This will require a coordinated effort of all stakeholders if we are meet our increasing demand for freshwater while allowing our estuaries to remain productive nurseries for blue crabs.

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