

# Estimating Relative Abundance of the Female Blue Crab Spawning Stock in North Carolina

**Daniel Rittschof, M. Zachary Darnell,<sup>1</sup> Kelly M. Darnell,<sup>1</sup> Margaret Goldman, Matthew B. Ogburn,<sup>2</sup> and Ruth McDowell<sup>3</sup>**

*Duke University Marine Laboratory, Nicholas School of the Environment, Beaufort, North Carolina, U.S.A.*

## Abstract

Accurate assessment of the spawning stock should be important in informing fisheries management decisions. The life history and behavior of blue crabs (*Callinectes sapidus*) makes assessment of the spawning stock complex. In North Carolina, female blue crabs undergo their terminal molt and mate from March through November. After a variable amount of time, their ovaries mature and they extrude their first clutch of eggs. Crabs that mature in the upper estuary move from low salinity (<20 ppt) to high salinity (>22 ppt) to release their first clutch of eggs. Crabs in good habitat then forage and produce subsequent clutches of eggs, continuing to move seaward with each subsequent clutch. Thus, at any particular location, different spawning crabs will be seen each month and will build up in high salinity areas in the sounds and in the coastal ocean. The spawning population peaks in number in August/September with some crabs releasing their first clutch and others releasing their second or higher clutch. Using blue crab bycatch data from Division of Marine Fisheries monthly gill net surveys may be helpful in estimating blue crab spawning stock. Gill net data show the monthly pattern of spawning stock movement from low to high salinity and the

---

<sup>1</sup>Present address: Marine Science Institute, The University of Texas at Austin, 750 Channel View Dr., Port Aransas, TX 78373, U.S.A.

<sup>2</sup>Present address: Savannah State University, Box 20228, 3219 College Street, Savannah, GA 31404, U.S.A.

<sup>3</sup>Present affiliation: Department of Biology, University of Alabama at Birmingham, Birmingham, AL 35294, U.S.A.

buildup of spawning stock in high salinity waters. The pattern in spawning females is correlated with the return of settlement-stage crab larvae from the coastal ocean to a tidally driven estuary.

## Introduction

The blue crab (*Callinectes sapidus*) fishery is North Carolina's most valuable fishery, with an average annual commercial harvest value of \$35 million during 1996-2005. According to the 2004 stock assessment, the population is declining, with a reduction in spawning stock biomass of 74% since 1999 (Eggleston et al. 2004). Commercial landings increased from 1986 to 1996, followed by a period of reduced landings in 2000-2002 and in 2004-2007. The 2007 fishery yielded the lowest landings since 1977 (9,707 metric tons compared to an average of 20,638 t), though landings increased in 2007 in part of the state. The North Carolina Division of Marine Fisheries lists the current stock status as "of concern." Although there is great uncertainty regarding current maximum sustainable yield (MSY) estimates due to modeling limitations and the influence of environmental variables on the population, estimates of MSY range from 11,793 t to 23,586 t per year. Despite modeling limitations, fishery-dependent and fishery-independent data indicate that current fishing pressure exceeds MSY (NCDMF 2007). At this point, the blue crab is on the brink of being considered overfished (NCDMF 2007).

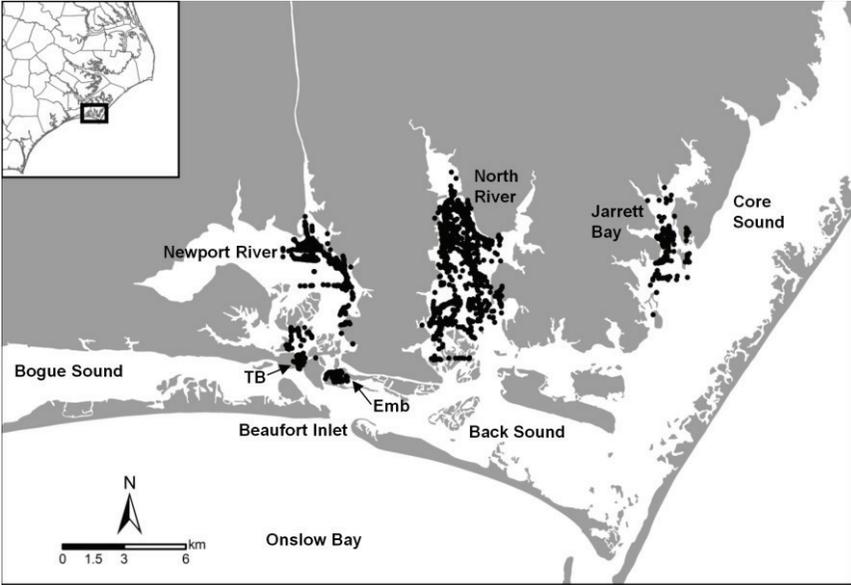
Although regulators acknowledge that management of fisheries requires a thorough understanding of the species' life history, key features of blue crab life history are missing (NCDMF 2004). It is known that females experience a terminal molt to maturity, mate, and store sperm. Females forage, mature their ovaries, and then extrude and attach a clutch of fertilized eggs to their abdomens where they are brooded until hatching. Little is known about individual female movements before or after hatching of a clutch of eggs. Most of the work on large-scale female movements has been done in the very large Chesapeake Bay and Albemarle Pamlico Estuarine System, where size, geometry, and huge numbers of crabs make following of individuals difficult. It is known that females with mature eggs undergo a spawning migration, in which they migrate seaward on ebb tides at night.

The initial hypothesis that females return to the upper estuary after spawning (Tankersley et al. 1998) has been rejected (Forward et al. 2005). The work of Forward et al. (2005), Hench et al. (2004), Darnell (2009), and Darnell et al. (2010a) indicates that crabs do not return to the low-salinity areas of the upper estuary. Rather, spawning female crabs forage in high-salinity habitat (inlets, sounds, coastal ocean) until they gain sufficient energy to extrude an additional clutch of eggs. These crabs continue to be most active on falling tides, which ensures that they continue to move seaward throughout the spawning season.

In a small, tidally driven estuary, the spawning migration moves females seaward throughout the spawning season (Rittschof 2004). We hypothesize that the spawning migration similarly moves females seaward throughout the entire spawning season in other locations. We postulate that crabs rapidly exit low-salinity habitat following oviposition and then have punctuated movements seaward. They may, for example, remain in an area foraging for several weeks while they build up energy stores, mature their ovaries, and extrude an additional clutch of eggs.

The migratory nature of the blue crab life cycle makes assessment of the spawning stock a complex task. Presently in North Carolina, June and September trawl surveys in the Pamlico Sound are used to assess spawning stock biomass. The survey is inadequate in many regards, including the following: (1) less than 1% of the female crabs captured in either trawl survey are ovigerous females; (2) most crabs captured in the September survey will not spawn until the following year (Darnell et al. 2009); (3) the survey is fixed in one area, independent of salinity, and not in blue crab habitat; (4) there are fisheries to the ocean side of the survey area; and (5) the survey does not take into account that crabs mature continuously from early spring (March) to late fall (November) (Dickinson et al. 2006; Ramach et al. 2009).

Our objectives are threefold. First, we develop a conceptual model for the female blue crab spawning migration based upon a mark-recapture study in a small, tidally driven estuary. We use mark-recapture approaches to understand these features of the life history that would be costly and virtually impossible in larger estuaries. Second, we apply that natural history information to examine two different methods (the standard trawl survey and monthly gill net bycatch data) of assessing the blue crab spawning stock in the Albemarle Pamlico Estuarine System (APES) of North Carolina. The APES is a vast (second largest estuary in the United States), mainly wind-driven estuarine system (Roelofs and Bumpus 1953, Luettich et al. 2002). Third, we use return of megalopae to Beaufort Inlet, North Carolina, as a measure of efficacy of a proposed method of sampling the spawning stock. Megalopal (settlement stage crabs) data from this inlet has a strong correlation with fisheries yields (Ogburn and Forward 2009). Two hypotheses have been put forth concerning the spawning stock/recruitment relationships to explain the timing of megalopal recruitment. The first hypothesis is that high crab settlement in North Carolina estuaries in the fall is due to peak spawning of blue crabs in the estuary in late summer/early fall. The alternative hypothesis is that peak settlement in the fall is due to continual spawning of blue crabs from spring to fall, with oceanographic conditions most favorable for inshore transport only in the fall (Eggleston et al. 2004). Given recent information on spawning biology of blue crabs (Darnell 2009, Eggleston et al. 2010), it is likely that peak spawning and oceanographic conditions are both involved. We assess these two



**Figure 1. Map of Beaufort Inlet drainage showing locations of crabs tagged in 2001 and 2002. Each dot represents the location of one tagged crab. TB: turning basin. Emb: embayment.**

hypotheses using Pamlico Sound gill net CPUE data and megalopal recruitment data from Beaufort Inlet. We stress that our goal is to provide insights to stock assessment scientists and fishery managers; we do not to attempt such stock assessments here.

## Materials and methods

### *Beaufort Inlet drainage*

The Beaufort Inlet drainage is an estuarine and sound system that makes up an area of approximately 225 square miles. Major features of this study area include the Newport River, North River, Jarrett Bay, Port of Morehead City turning basin, a high-salinity embayment in the Rachel Carson National Estuarine Research Reserve, Onslow Bay, and two fishing piers to the west of the inlet (Fig. 1). Beaufort Inlet drains to the south between Shackleford Banks and Bogue Banks into Onslow Bay. Approximately 85% of the flow in the drainage is due to tidal forcing (Hench and Luettich 2003).

In 2001 and 2002, mature female blue crabs were captured in the upper estuary bays (Newport River, North River, Jarrett Bay) and off

**Table 1. Numbers of crabs marked and recaptured for each of the tagging locations in 2001 and 2002.**

Year	Location	Marked	Recaptured	Recapture rate
2001	Embayment	667	297	44.53%
	Newport River	779	33	4.24%
	North River	456	105	13.89%
2002	Embayment	923	311	33.69%
	Jarrett Bay	1,235	60	4.86%
	Newport River	951	49	5.15%
	North River	930	70	7.53%

the Onslow Bay fishing piers. Migrating ovigerous crabs were captured in the turning basin and in Radio Island channel from a boat as they swam at the surface. Mature females were also captured in the Rachel Carson embayment around the times of nocturnal low tides using a dip net. Egg stage was noted for each crab, and for crabs captured in the three main bays and the embayment, each crab was marked with uniquely numbered across-the-back tags composed of a poker chip with 18 g plastic-coated copper wire looped around the large lateral spines. A total of 5,941 female crabs were tagged and released immediately at the location of capture (Fig. 1). Recapture data were obtained from local fishermen, crabbers, and other scientists working in the area. Returns were monitored and documented. A total of 925 crabs were recaptured, for a total recapture rate of 15.6% (Table 1). Additionally, in collaboration with an offshore fisherman, pots were set offshore and egg status was recorded for female crabs caught in 10 to 15 meters of water in Onslow Bay. Egg state was noted at times of capture.

### ***Program 915 gill net survey***

To better understand the distribution and abundance of the blue crab spawning population, data were obtained and analyzed from the North Carolina Department of Marine Fisheries Pamlico Sound Independent Gill Net Survey (Program 915; Paramore 2009). Field sampling for this survey began in May 2001 with four objectives: (1) calculate annual indices of abundance for Pamlico Sound for Atlantic croaker (*Micropogonias undulatus*), bluefish (*Pomatomus saltatrix*), red drum (*Sciaenops ocellatus*), southern flounder (*Paralichthys lethostigma*), spot (*Leiostomus xanthurus*), weakfish (*Cynoscion regalis*), spotted seatrout (*Cynoscion*

*nebulosus*), and striped bass (*Morone saxatilis*); (2) supplement samples for age, growth, and reproduction studies; (3) identify bycatch problems in Pamlico Sound; and (4) characterize habitat utilization in Pamlico Sound. Sampling was originally conducted in all 12 months of the year but due to extremely low catches and unsafe working conditions the sampling season was shortened in 2002 with sampling no longer occurring between December 15 and February 14.

The gill net survey employs a stratified random sampling design and the sampling area consists of two regions: eastern Pamlico Sound adjacent to the Outer Banks from southern Roanoke Island to the northern end of Portsmouth Island, and western Pamlico Sound from Stumpy Point Bay to Abel's Bay. The area extends into both the Oregon and Hatteras Inlet blue crab spawning sanctuaries, but lies completely outside the Ocracoke Inlet sanctuary. Twice monthly from March to November, and once per month in February and December, four areas within the grid were sampled in both the eastern and western regions. For each area selected, both shallow ( $\leq 1.8$  m) and deep ( $> 1.8$  m) strata were sampled with a separate array of nets, each array consisting of 27.3 m segments of 7.6, 8.9, 10.2, 11.4, 12.7, 14, 15.2, and 16.5 cm stretched mesh webbing, totaling 218.4 m of gill nets. Each month, a total of 16 core samples were collected in each region (eight in February and December).

Gill net survey data on female crabs caught in east and west Pamlico Sound, from May 2001 to November 2006, were extracted from the survey database, and the numbers of immature, non-ovigerous mature, and ovigerous crabs were calculated for each month of each year. Ovigerous crabs caught on the east side were further classified by the stage of embryonic development, which can be inferred from the color of the egg mass. The survey recorded egg mass color as either yellow-orange (early stage embryos) or brown-black (late-stage embryos). Female crabs were coded by maturity stage and their locations mapped using ArcMap 9.2. To investigate temporal and spatial trends in mature female crabs caught in the gill net survey, mean catch per unit effort of immature, mature, and ovigerous crabs was calculated for each month by dividing the number of crabs caught by the number of samples taken that month (number of crabs caught per month per number of samples per month). Several months were short of the full sixteen samples (i.e., eight samples in February and eight in December), most likely due to weather conditions (K. West, North Carolina Division of Marine Fisheries, pers. comm.). Bottom salinity was also measured in collected samples.

### ***Post-larval (megalopae) settlement data***

To test the two hypotheses concerning the blue crab spawning stock/recruitment relationship and the timing of blue crab post-larval (megalopae) recruitment, settlement was quantified at the Duke University Marine Laboratory dock, located approximately 3 km inshore of

Beaufort Inlet, daily from June 2 to November 15 in 2004 and 2005 and from June 1 to November 15 in 2006. Biweekly settlement numbers were compared to CPUE of mature females in east Pamlico Sound during 2004, 2005, and 2006.

To quantify settlement, cylindrical “hogs hair” collectors (Metcalf et al. 1995) were utilized. These collectors consisted of PVC pipe weighted with concrete to insure the pipe hung vertically. Collectors were submerged 1 m below mean low water for approximately 24 hours. Following retrieval, they were soaked in freshwater for a minimum of 20 minutes and sprayed with freshwater to remove megalopae, which were identified and quantified using a dissecting microscope.

If the first hypothesis (that fall settlement is due to peak spawning in the estuary in late summer/early fall) is correct, we expect megalopal return to be related to monthly ovigerous female CPUE one to two months earlier. Alternatively, if the second hypothesis (that peak settlement in the fall is due to continual spawning of blue crabs from spring to fall, with oceanographic conditions most favorable for inshore transport only in the fall) is correct, we expect cumulative CPUE to peak in late summer/early fall, one to two months before settlement peaks in the estuary.

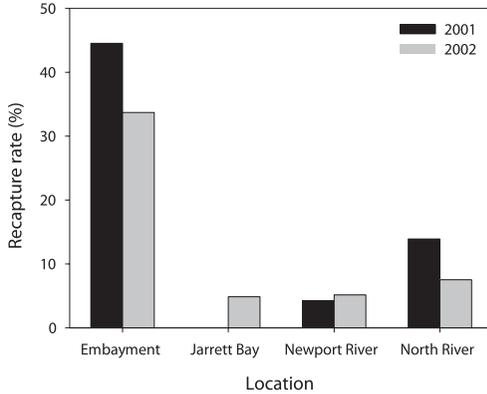
## Results

### ***Mark-recapture in Beaufort Inlet drainage***

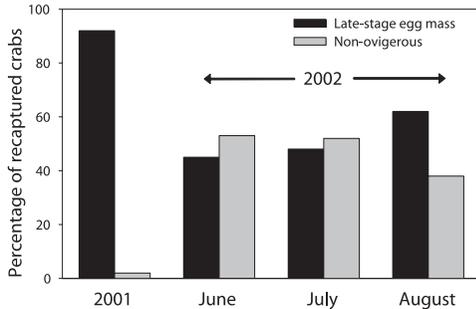
We compared recapture rates of ovigerous crabs marked and released in the upper estuary and ovigerous crabs marked and released in the high salinity embayment for three months. During each month, crabs were tagged in one of the three upper estuary areas (Newport River, North River, Jarrett Bay), and in the embayment. Recaptures of crabs in the upper estuary were between 4% and 14%, while recaptures in the embayment for the same time intervals were between 33% and 45% (Fig. 2). Of 1,590 crabs marked in the high salinity embayment, seven crabs (0.4%) were recaptured in the upper estuary areas. Even though we had 30-50% recapture in the high salinity embayment, essentially all of the female crabs left the embayment when embryos reached the late stages of development.

We next compared two years of data for crabs migrating at the surface at night in the turning basin (Fig. 3). One year (2001) had normal rainfall, whereas the other (2002) experienced a drought. In the year with normal rainfall over 90% of the crabs captured while migrating had late-stage egg masses. In contrast, approximately 50% of the crabs migrating during the drought year were not ovigerous.

We traveled the region in the vicinity of the Beaufort Inlet at night on ebb tides looking for migrating crabs at the surface. We found the



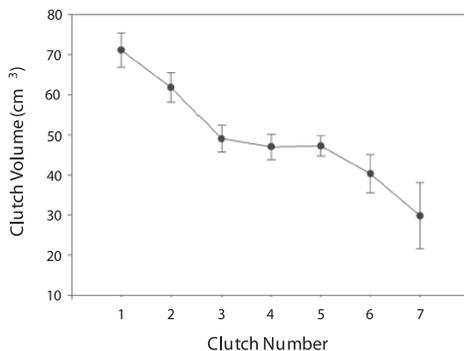
**Figure 2. Recapture rates of female crabs tagged in the high-salinity embayment and the three upper estuary bays. Note that no crabs were tagged in Jarrett Bay in 2001. Effort was approximately equal in all areas.**



**Figure 3. Percent of crabs migrating with a late-stage egg mass and with no egg mass during a normal rainfall year (2001), and during 3 months of a drought year (2002).**

locations where sightings were relatively common: the Port of Morehead City turning basin, the Pivers Island Bridge (Tankersley et al. 1998), and Radio Island channel. All crabs found swimming at the surface were females, and in two nights of traveling the same areas on flood tides, no crabs were observed migrating on the surface. The only ovigerous crabs marked in the upper estuary and recaptured after larval release were crabs recaptured in the turning basin while migrating and in foraging habitat in the Rachel Carson embayment.

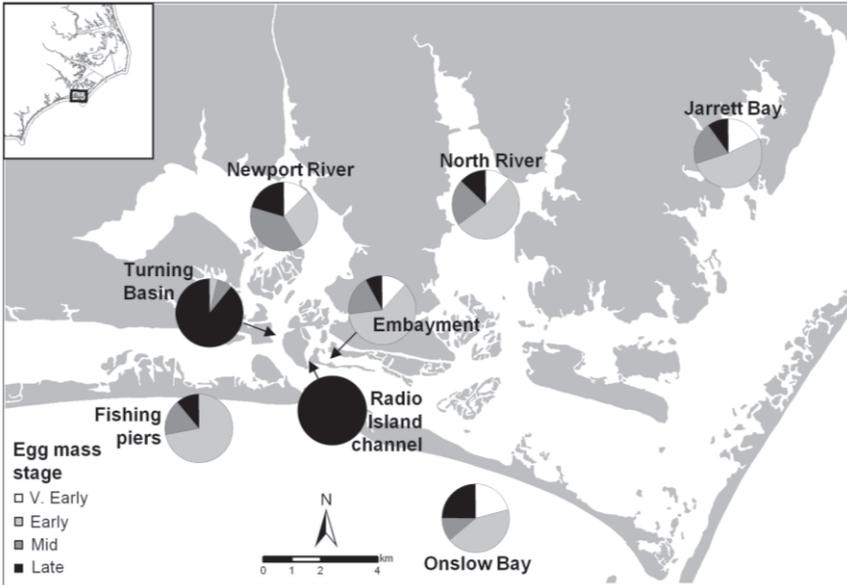
At the start of the study, the lore was that a female blue crab had a single clutch of eggs. Subsequently Hines et al. (2003), Hench et al.



**Figure 4. Mean clutch volume ( $\pm$ SE) over successive clutches for blue crabs producing more than two clutches in captivity. All stages of embryonic development and all crab sizes are included. Crabs were retained in the field individually in submerged minnow traps. (From Dickinson et al. 2006; axis labels have been redrawn.)**

(2004), Dickinson et al. (2006), and Darnell et al. (2009) reported that blue crabs had multiple clutches of eggs, often in rapid succession. Female blue crabs confined individually in the field as described by Dickinson et al. (2006) and Darnell et al. (2009) produced multiple clutches of eggs, up to seven clutches in a single season, and some crabs spawned during two spawning seasons (Darnell et al. 2009). In all recent studies of blue crab clutch production, clutch volume was correlated with crab size, but decreased with clutch number for all size classes of crabs (Dickinson et al. 2006; Darnell et al. 2009, 2010b) (Fig. 4).

In the summer, it generally takes about 12 days for blue crab embryos to develop. Development within an egg mass is synchronous. Newly extruded egg masses are yellow, and the egg mass color progresses to orange, brown, and finally black as the embryos develop. Egg mass color was recorded for all areas where crabs were caught (Fig. 5). All developmental stages were observed at all locations except the fishing piers, the turning basin, and Radio Island channel. At the fishing piers, primarily orange egg masses were seen, with some brown and black egg masses. No yellow egg masses were seen at the fishing piers. The turning basin had no yellow egg masses and only a few orange and brown egg masses. The vast majority of egg masses captured in the turning basin were black. For the very small number of crabs (<20) observed in the Radio Island channel region, only black egg masses were observed.

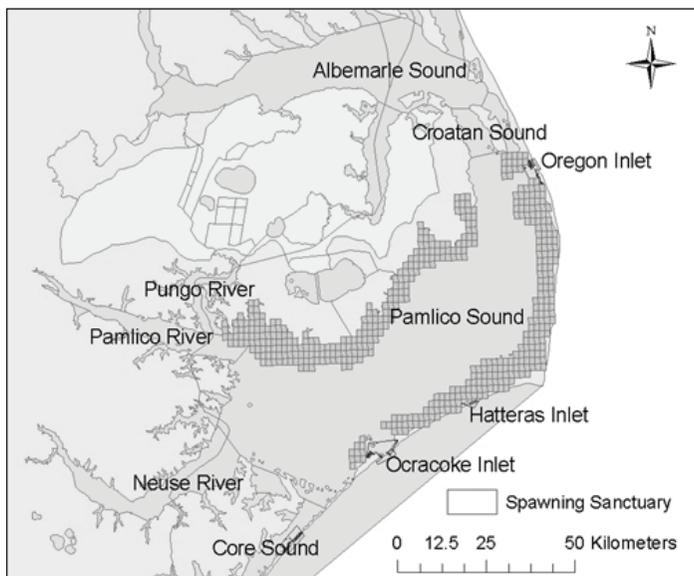


**Figure 5. Distribution of egg mass stages at each capture location in 2001 and 2002.**

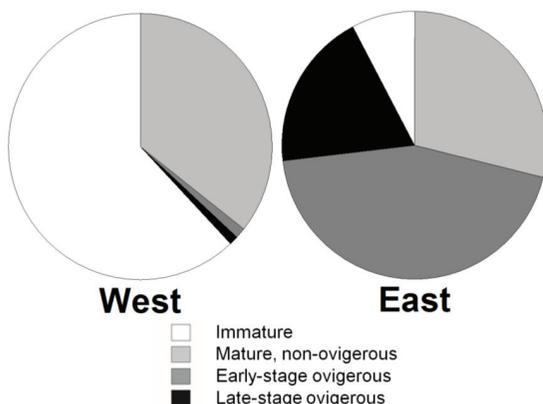
### ***Pamlico Sound gill net survey***

The Division of Marine Fisheries gill net survey captured large numbers of female crabs as bycatch. The nets were set in crab habitat on the west and east sides of Pamlico Sound (Fig. 6). Salinity on the west side of the sound was usually less than 21 ppt while the salinity on the east side of the sound was 30-35 ppt. The gill net survey caught predominantly immature females in west Pamlico Sound and mature females in east Pamlico Sound (Fig. 7). On the east side, the percentage of mature females with eggs varies from month to month, but in the spring and summer months the percentage of ovigerity can be as high as 96%. On the west side, mature females rarely have eggs. The presence of ovigerous crabs on the west side was correlated with salinity conditions. Ovigerous crabs were caught on the west side in three of the six years surveyed (15 in 2001, 14 in 2002, and 3 in 2004.) Their presence was likely due to low freshwater runoff, providing the salinity conditions necessary for embryonic development, ~20-25 ppt (Warner 1976, as cited in Ballance and Ballance 2004). Ovigerous crabs were found on average at salinity of 21 ppt.

Of all females caught in the gill net survey (approximately 1,000 on each side), 2.4% of those caught on the west side were ovigerous and



**Figure 6. Sampling locations (squares) for North Carolina Division of Marine Fisheries Program 915 gill net survey in Pamlico Sound. The locations of the spawning sanctuaries are shown around Oregon, Hatteras, Ocracoke, and Drum inlets.**



**Figure 7. Proportion of females by maturity and egg mass stage for the east Pamlico Sound and west Pamlico Sound Program 915 gill net survey from 2001-2006.**

65% of those caught on the east side were ovigerous (Fig. 7). On the east side, ovigerous crabs with early stage embryos occurred about twice as frequently as ovigerous crabs with late-stage embryos. As predicted, the east gill net survey caught the highest percentage of mature and ovigerous females.

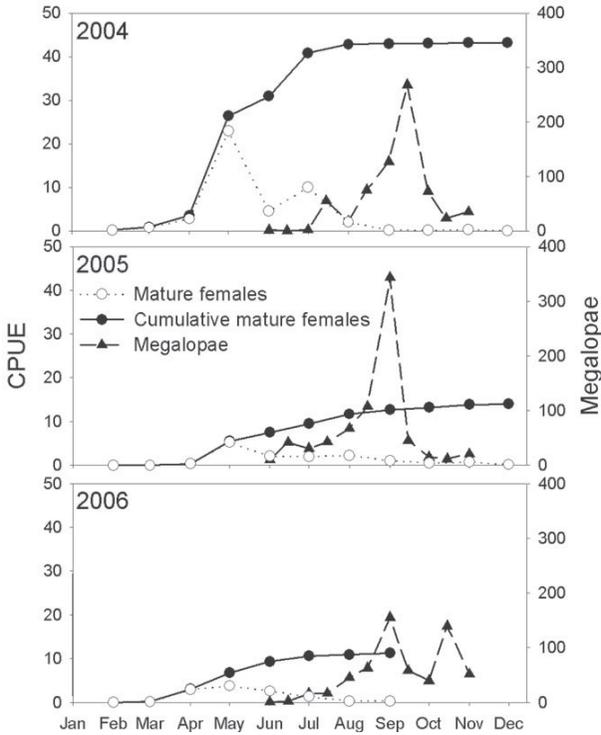
Three years of megalopal abundance data collected at the Duke Marine Lab dock were compared with mature female CPUE from the gill net survey on the east side of the sound (Fig. 8). These three years were used because they were the only years for which we had a complete megalopal data set for the entire spawning season. In the gill net survey, seasonal peaks in abundance of mature females on the spawning grounds have varied from year to year, generally occurring in April/May and/or July. When cumulative CPUE is calculated, it levels off in late summer/early fall. Total numbers of mature females were highest in 2004, intermediate and ~34% of the 2004 levels in 2005, and ~28% of 2004 levels in 2006. Megalopal abundance lagged behind mature female abundance, was highest in 2005, ~85% of 2005 abundance in 2004, and approximately 50% of 2005 megalopal abundance in 2006.

## Discussion

Based upon our results of several years of capturing, marking, and recapturing crabs throughout the Beaufort Inlet drainage, we propose an operational model of the female blue crab spawning migration. We suggest that the specified components of our model could form the basis for developing a future stock assessment to estimate the spawning stock biomass of blue crab. In addition, interpreting data in the context of the model would be a starting point for a life history based fishery management strategy. However, both of these future important activities are beyond the scope of this study.

In the model females molt to maturity and mate during all months when blue crabs are active. In North Carolina, females reach maturity, usually in water between 0 and 20 ppt salinity and mate from mid-March to mid-November. In the spring, molting is relatively synchronous and becomes less synchronous as the season progresses. Maximum numbers of females molt from April to October (Darnell et al. 2009, Ramach et al. 2009). A smaller number of crabs mature and mate in high salinity water (Ramach et al. 2009). Depending on the time of year and temperature, females forage in the vicinity of where they mated for 3 to 12 weeks in the summer and potentially longer in cooler seasons or regions (Darnell 2009).

Around the time of extrusion of the first clutch of eggs, crabs move to salinity of approximately 21 ppt or higher. Crabs in lower salinity and in non-foraging habitat migrate rapidly seaward until they encounter foraging habitat. When crabs are in foraging habitat, swimming fre-



**Figure 8. Monthly CPUE of mature females, cumulative total CPUE of mature females, and biweekly megalopal settlement for three years. Mature female data are from the Program 915 eastern Pamlico Sound gill net survey. Megalopal data are from the Duke Marine Lab dock.**

quency decreases dramatically and they forage until embryos mature and eggs are close to hatching (Rittschof 2004, Darnell 2009, Ramach et al. 2009). Seaward movement activity increases as the embryos mature (Hench et al. 2004, Darnell 2009). Crabs leave foraging habitat when eggs are within 1-2 days of hatching. Ebb tide transport is obvious down migration corridors, areas of high ebb current velocity, to the next foraging habitat (Hench et al. 2004, Rittschof 2004, Darnell 2009).

Due to short distances and multiple clutches of eggs in the small strongly tidal Beaufort Inlet drainage, most female crabs have migrated out of the estuary and into the ocean by September (Rittschof 2004). In a huge system like the Albemarle Pamlico Estuarine System, crabs migrate to the high salinity waters on the inside of the barrier islands and the probably into and through the spawning sanctuaries to the coastal

ocean. Crabs do not discriminate between sounds and the coastal ocean. Where crabs end up depends upon currents and the quality of the foraging habitat.

Thus, in the model, spawning female blue crabs are continuously migrating seaward throughout the blue crab's active season (Hench et al. 2004, Forward et al. 2005). Movement in high-salinity water is into and out of foraging habitats and depends on currents. Because of production of multiple clutches, spawning female crabs accumulate in high salinity water over time.

The spawning stock for the present year is composed of crabs that matured from the previous fall until the beginning of September (Darnell et al. 2009). Relatively few crabs spawn over two seasons (mainly those that mature in late July and August) (Darnell et al. 2009). Their contribution in the second spawning season is made early in the spring and is relatively low because fecundity drops with each successive clutch. Thus, in most years the east Pamlico Sound gill net survey should be useful in estimating spawning stock biomass and the cumulative CPUE of mature females caught in the survey should be useful in predicting recruitment. In years of extreme drought, the western Pamlico Sound gill net survey would also add information. If the high salinity water on the east side of the sound were closed to crab fishing, the eastern Pamlico Sound gill net survey would be a reliable estimate of the post-fishery spawning stock. Thus, the cumulative total of mature females spawning that season and their total fecundity is the spawning stock biomass. By totaling monthly CPUE from the eastern Pamlico Sound gill net survey over time, one could obtain an estimate of the total number of spawning crabs. Using mature size and time of year, fecundity could be estimated.

Presently, spawning stock biomass is estimated in North Carolina using a fishery-independent trawl survey. While trawl surveys are often used to assess blue crab spawning stocks (e.g., Lipcius and Van Engel 1990, Lipcius and Stockhausen 2002, Kahn and Helser 2005), the trawl survey used in North Carolina may not be adequate for assessing the spawning stock in Pamlico Sound. The trawl survey is a fixed location on the west side of Pamlico Sound, is poorly timed conducted only in June and September each year, ignores the spawning biology of blue crabs, and is taken in the middle of the fishery. Trawls take place in relatively deep water that is usually low-salinity, and the trawls yield less than 1% ovigerous females at both time intervals. The June census misses the spring (March to June) pulse of ovigerous crabs that have already moved to high-salinity water. Because they will have multiple clutches of eggs and many will finish spawning in October (Dickinson et al. 2006, Darnell et al. 2009) these crabs may be major contributors to the spawning stock. The September trawl survey measures some percentage of crabs that will spawn that year and some proportion of the next year's spawning

stock. Crabs that molt to maturity in September do not extrude their first clutch until the following year (Darnell et al. 2009). Thus, some proportion of females captured by the trawl survey in September is females that molted to maturity prior to September and the rest are crabs that molted to maturity in September and will contribute to spawning stock for the subsequent year. We estimate that less than 1% of the present year's spawning stock is represented in the September trawl survey. Thus, if the trawl survey were to be a useful starting point it would need to be adjusted to account for these shortcomings. We suggest that an alternative starting point might be blue crab bycatch data from monthly gill net surveys. Using information from the west and east sides of the survey separately enables a continuous assessment of spawning stock in relation to the proposed conceptual model.

After release, larvae develop on the continental shelf through seven zoeal stages in four to five weeks (Epifanio 1995). Settlement stage larvae re-enter the estuary and settle in benthic habitats such as seagrass or shallow detrital habitats (Etherington and Eggleston 2003). Re-entrance into the estuary is associated with southward, alongshore wind events, and occurs in discrete pulses and does not necessarily occur in parent estuaries (Epifanio 1995). In North Carolina, post-larval settlement is highest in Pamlico Sound in the fall (Eggleston et al. 2004) and dependent upon storm forcing (Eggleston et al. 2010). Near Beaufort Inlet, peak settlement occurs in September/October (Dudley and Judy 1971, Forward et al. 2004). In 2004, 2005, and 2006, settlement in the Newport River Estuary near Beaufort Inlet remained low until mid August, with peak settlement in September/October. Peak spawning is predicted to occur 4-5 weeks before this, in August (Eggleston et al. 2004).

As already discussed, CPUE of mature females in the east side gill net survey peaked in May of these years. Cumulative CPUE, on the other hand, indicates peak numbers of spawning females in late summer/early fall. High settlement in the fall may also be attributed to retention of settlement-stage larvae in coastal waters during the summer (Tilburg et al. 2007) and oceanographic conditions most favorable for inshore transport in the fall (Eggleston et al. 2004). This supports the hypothesis that patterns in settlement are a function of continual spawning from spring to fall, with peak numbers of spawning females in late summer/early fall and reentrance of settlement stage larvae about four weeks later during favorable wind and tidal conditions (Epifanio 2003; Eggleston et al. 2004, 2010).

In order to sustainably manage the blue crab fishery, an accurate spawning stock assessment would be helpful. Methods for such a stock assessment could be based on the life history and spawning biology of the species and detailed data already collected as part of finfish management programs. Those interested in modeling blue crab spawning stock might consider this proposal as an option.

## Acknowledgments

The authors would like to thank North Carolina Sea Grant for providing funding for this study (Blue Crab Research Program grants 02-BIOL-04, 04-BIOL-05, 06-BIOL-04). We are grateful to the many crabbers and crab-houses that assisted with the mark-recapture study, especially Anthony Austin, Anthony Sawyer, Danny Rimmer, Ray Golden, Ernie Small, C&S Seafood, and Newman Seafood. Numerous Duke University Marine Laboratory undergraduate and graduate students helped mark crabs in the embayment over the course of the study, and North Carolina Division of Marine Fisheries personnel provided the gill net survey data used in the analysis.

## References

- Ballance, E.S., and E.B. Ballance. 2004. Blue crab sampling in the vicinity of the Ocracoke and Hatteras Inlet blue crab sanctuaries using crab pots. Final report for contract 02-POP-03 to the Blue Crab Research Program, North Carolina Sea Grant. 18 pp. Unpublished.
- Darnell, M.Z. 2009. Spawning biology of female blue crabs, *Callinectes sapidus*. Ph.D. dissertation, Duke University, Durham.
- Darnell, M.Z., D. Rittschof, K.M. Darnell, and R.E. McDowell. 2009. Lifetime reproductive potential of female blue crabs *Callinectes sapidus* in North Carolina, USA. *Mar. Ecol. Prog. Ser.* 394:153-163. doi:10.3354/meps08295
- Darnell, M.Z., D. Rittschof, and R.B. Forward Jr. 2010a. Endogenous swimming rhythms underlying the spawning migration of the blue crab, *Callinectes sapidus*: Ontogeny and variation with ambient tidal regime. *Mar. Biol.* 157(11):2415-2425. doi:10.1007/s00227-010-1506-5
- Darnell, M.Z., K.M. Darnell, R.E. McDowell, and D. Rittschof. 2010b. Postcapture survival and future reproductive potential of ovigerous blue crabs *Callinectes sapidus* caught in the central North Carolina pot fishery. *Trans. Am. Fish. Soc.* 139:1677-1687.
- Dickinson, G.H., D. Rittschof, and C. Latanich. 2006. Spawning biology of the blue crab, *Callinectes sapidus*, in North Carolina. *Bull. Mar. Sci.* 79:273-285.
- Dudley, D.L., and M.H. Judy. 1971. Occurrence of larval, juvenile, and mature crabs in the vicinity of Beaufort Inlet, North Carolina. NOAA Technical Report, NMFS SSRF-637. 10 pp.
- Eggleston, D.B., E.G. Johnson, and J.E. Hightower. 2004. Population dynamics and stock assessment of the blue crab in North Carolina. Final report for contracts 99-FEG-10 and 00-FEG-11 to the North Carolina Fisheries Resource Grant Program, North Carolina Sea Grant. 230 pp. Unpublished.
- Eggleston, D.B., N.B. Reynolds, L.L. Etherington, G.R. Plaia, and L. Xie. 2010. Tropical storm and environmental forcing on regional blue crab (*Callinectes sapidus*) settlement. *Fish. Oceanogr.* 19:89-106. doi:10.1111/j.1365-2419.2009.00530.x

- Epifanio, C.E. 1995. Transport of blue crab (*Callinectes sapidus*) larvae in the waters off mid-Atlantic states. *Bull. Mar. Sci.* 57:713-725.
- Epifanio, C.E. 2003. Spawning behavior and larval ecology: A brief summary. *Bull. Mar. Sci.* 72:322-330.
- Etherington, L.L., and D.B. Eggleston. 2003. Spatial dynamics of large-scale, multistage crab (*Callinectes sapidus*) dispersal: Determinants and consequences for recruitment. *Can. J. Fish. Aquat. Sci.* 60:873-887. doi:10.1111/j.1365-2419.2009.00530.x
- Forward, R.B., J.H. Cohen, M.Z. Darnell, and A. Saal. 2005. The circatidal rhythm in vertical swimming of female blue crabs, *Callinectes sapidus*, during their spawning migration: A reconsideration. *J. Shellfish Res.* 24:587-590.
- Forward, R.B., J.H. Cohen, R.D. Irvine, J.L. Lax, R. Mitchell, A.M. Schick, M.M. Smith, J.M. Thompson, and J.I. Venezia. 2004. Settlement of blue crab *Callinectes sapidus* megalope in a North Carolina estuary. *Mar. Ecol. Prog. Ser.* 269:237-247. doi:10.3354/meps269237
- Hench, J.L., and R.A. Luettich. 2003. Transient tidal circulation and momentum balances at a shallow tidal inlet. *J. Phys. Oceanogr.* 33:913-932. doi:10.1175/1520-0485(2003)33<913:TTCAMB>2.0.CO;2
- Hench, J.L., R.B. Forward, S.D. Carr, D. Rittschof, and R.A. Luettich. 2004. Testing a selective tidal-stream transport model: Observations of female blue crab (*Callinectes sapidus*) vertical migration during the spawning season. *Limnol. Oceanogr.* 49:1857-1870. doi:10.4319/lo.2004.49.5.1857
- Hines, A.H., P.R. Jivoff, P.J. Bushmann, J. van Montfrans, S.A. Reed, D.L. Wolcott, and T.G. Wolcott. 2003. Evidence for sperm limitation in the blue crab, *Callinectes sapidus*. *Bull. Mar. Sci.* 72:287-310.
- Kahn, D.M., and T.E. Helser. 2005. Abundance, dynamics and mortality rates of the Delaware Bay stock of blue crabs, *Callinectes sapidus*. *J. Shellfish Res.* 24:269-284.
- Lipcius, R.N., and W.T. Stockhausen. 2002. Concurrent decline of the spawning stock, recruitment, larval abundance, and size of the blue crab *Callinectes sapidus* in Chesapeake Bay. *Mar. Ecol. Prog. Ser.* 226:45-61. doi:10.3354/meps226045
- Lipcius, R.N., and W.A. Van Engel. 1990. Blue crab population dynamics in Chesapeake Bay: Variation in abundance (York River, 1972-1988) and stock-recruit functions. *Bull. Mar. Sci.* 46:180-194.
- Luettich, R.A., S.D. Carr, J.V. Reynolds-Fleming, C.W. Fulcher, and J.E. McNinch. 2002. Semi-diurnal seiching in a shallow, micro-tidal lagoonal estuary. *Cont. Shelf Res.* 22:1669-1681. doi:10.1016/S0278-4343(02)00031-6
- Metcalf, K.S., J. von Montfrans, R.N. Lipcius, and R.J. Orth. 1995. Settlement indices for blue crab megalopae in the York River, Virginia: Temporal relationships and statistical efficiency. *Bull. Mar. Sci.* 57:781-792.
- NCDMF. 2004. North Carolina fishery management plan: Blue crab. North Carolina Division of Marine Fisheries, Morehead City. 134 pp.

- NCDMF. 2007. Stock status of the blue crab in North Carolina, 2007. North Carolina Division of Marine Fisheries. Accessed Dec. 2010: <http://www.ncfisheries.net/stocks/index.html>.
- Ogburn, M.B., and R.B. Forward. 2009. Ingress of brachyuran crab post-larvae to the Newport River estuary. *Estuar. Coasts* 32:309-318. doi:10.1007/s12237-009-9136-1
- Paramore, L. 2009. Pamlico Sound independent gill net survey. North Carolina Division of Marine Fisheries final report for grant F-70 to the U.S. Fish and Wildlife Service. 47 pp. Unpublished.
- Ramach, S.M., M.Z. Darnell, N.G. Avissar, and D. Rittschof. 2009. Habitat use and population dynamics of blue crabs, *Callinectes sapidus*, in a high-salinity embayment. *J. Shellfish Res.* 28:635-640. doi:10.2983/035.028.0328
- Rittschof, D. 2004. Migration and reproductive potential of mature female blue crabs. Final report for contract 02-Biol-04 to the North Carolina Fisheries Blue Crab Research Grant Program, North Carolina Sea Grant. 53 pp. Unpublished.
- Roelofs, E.W., and D.F. Bumpus. 1953. The hydrography of Pamlico Sound. *Bull. Mar. Sci. Gulf Carib.* 3:181-205.
- Tankersley, R.A., M.G. Wieber, M.A. Sigala, and K.A. Kachurak. 1998. Migratory behavior of ovigerous blue crabs *Callinectes sapidus*: Evidence for selective tidal-stream transport. *Biol. Bull.* 195:168-173. doi:10.2307/1542824
- Tilburg, C.E., A.I. Dittel, and C.E. Epifanio. 2007. Retention of crab larvae in a coastal null zone. *Estuar. Coast. Shelf Sci.* 72:570-578. doi:10.1016/j.ecss.2006.11.030
- Warner, W.W. 1994. Beautiful swimmers: Watermen, crabs, and the Chesapeake Bay. Little, Brown and Company, New York.