APPENDIX A.3

Post-larval Collection
Final Report

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Blue crab post-larval immigration into an estuary

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Abstract

Postlarval immigration to estuaries is a critical transition in the life cycle of blue crabs that likely plays an important role in determining population size and spatial distribution. Consequently, understanding the temporal and spatial dynamics of postlarval immigration and how best to monitor these dynamics could be of great benefit to fishery managers. Seasonal immigration of postlarvae (megalopae) through Beaufort Inlet into the Newport River estuary was determined from June 1 to November 15, 2006 at the Duke University Marine Lab (DUML) dock and from June 1 to November 5, 2006 at a coastal site (Sportsman’s pier), completing a 3 year comparison of settlement at these two sites. Correlations between megalopal settlement and NC fishery landings were updated to include 2006 landings data. Our 11-year data set collected at DUML was used to examine the optimal timing and duration for annual monitoring of blue crab postlarval immigration and several alternatives to daily sampling were assessed to determine the feasibility of reducing sampling effort. Finally, megalopal settlement was determined at three additional sites within the Newport River estuary (Morehead channel, Radio Island channel and Shackleford channel) from August 14 to August 24 and September 20 to October 3, 2006 to determine the spatial distribution of immigration across the estuary.

Results are summarized as follows:

1. Moderate settlement began at the estuarine site on July 17 with the majority of settlement occurring from late August to early November.
2. High settlement events at the estuarine site were associated with neap tides and winds from the south (as expected), whereas high settlement at the coastal site was correlated with spring tides.
After removing one outlier, there are significant regressions for megalopal settlement from September to November at DUML and fishery landings (kg/trip) statewide and for the local estuary system. These equations allow us to predict landings in 2007 and 2008.

Over three years of sampling from June – November (2004-2006), peak settlement occurred during a 45-day period from August 22 to October 5 (63% of total) with a similar percentage of the remaining settlement before and after those dates. An optimal annual sampling period would be from August 1 to October 31.

Annual postlarval immigration is best measured using daily sampling. The best alternative sampling strategy assessed in this report is to sample 5 consecutive days during the week, leaving collectors in the water over the weekend.

Megalopal settlement was higher on the western side of Beaufort Inlet, suggesting an offshore source on that side of the inlet or active selection of an estuarine water mass.
Introduction

The Atlantic blue crab (*Callinectes sapidus* Rathbun) supports one of the most important commercial and recreational fisheries in NC. Annual variability in adult populations is a challenge to Fishery Managers, who do not yet have the tools to predict year class strength. Blue crabs have a complex life cycle in which adults are most abundant in low salinity regions of estuaries and females migrate to the coast following mating for larval release in high salinity areas (Pearson 1948; Van Engel 1958; McConaugha et al. 1983, Tankersley et al. 1998). Larval release is greatest at Beaufort, NC in late July and early August (R. Tankersley personal communication).

After hatching, larvae are advected away from shore, where they develop through 7 zoeal stages and 1 postlarval (megalopal) stage (Costlow and Bookhout 1959; Sulkin 1975, 1978). Immigration back to the entrance of an estuary occurs at the megalopal stage and is likely controlled by Ekman currents generated by wind events (Epifanio 1995; Epifanio and Garvine 2001). Transport up-estuary against net seaward currents is achieved by flood tide transport (FTT) in which megalopae move up into the water column during night-time flood tides and remain on the bottom during ebb tides and during the day (Epifanio et al. 1984; Brookings and Epifanio 1985; Mense and Wenner 1989; Little and Epifanio 1991; DeVries et al. 1994, Olmi 1994; Lochman et al. 1995). Inside an estuary, megalopae metamorphose and reside in beds of submerged aquatic vegetation through the 5\textsuperscript{th} instar (e.g. Orth and van Montfrans 1987; Lipcius et al. 1990; Etherington and Eggleston 2003) after which juveniles migrate to low salinity water and recruit into the fishery about 2 years later.
The transport of megalopae from offshore developmental areas to estuarine nursery habitats is a critical phase of the blue crab life cycle. An important question regarding postlarval immigration into estuaries is whether the pattern of high settlement during neap tides observed by Forward et al. (2004) over a 7 year period was the result of FTT behaviors within the estuary or the result of arrival of postlarvae at the coast during neap tides. Our previous work (Forward 2006) in 2005 suggested that abundance at the coast was significantly, but only weakly, correlated with abundance in the estuary and that the pattern of settlement during neap tides was only observed at the estuarine site. The first objective of this study was to conduct a second year of concurrent sampling at a coastal and an estuarine site throughout the recruitment season to confirm this observation.

A standard method for determining the relative abundance of megalopae entering an estuary is to quantify the number settling each night on a passive “hog’s hair” collector (Metcalf et al. 1994). In previous studies (Forward et al. 2004; Forward 2006), we determined the total postlarval settlement during the fall (September to early November) at the Duke University Marine Laboratory (DUML) dock (Table 1). With the exception of one outlier, these data are significantly correlated with fishery landings both statewide and in the local estuary and with juvenile and adult fishery independent surveys (Forward 2006). The equation of the regression line enables us to predict the landings 2 years in advance. The second objective of this study was to update these data by adding an additional data point and extending our predictions.

Long-term settlement data sets are time-consuming to collect, but are essential for determining the relationships between life history stages. For long-term sampling to
continue in an efficient manner, it is necessary to determine the optimal timing and
duration of sampling. Daily sampling, as has been carried out in the 11 years we have
studied postlarval settlement of blue crabs at DUML, is labor intensive and could
potentially be replaced by a sampling strategy that reduces effort while still providing
useful data. The third objective of this study was to determine the optimal timing and
duration of sampling as well as the least intensive sampling strategy that provides useful
data.

The spatial distribution of megalopae entering an estuary is another important
aspect of postlarval immigration that is poorly understood. Because nursery habitats are
not evenly distributed across the Newport River estuary and megalopae are not capable of
swimming against currents, successful location of these habitats may depend on where
megalopae enter through Beaufort Inlet. One possibility is that megalopae have an equal
probability of entering through any part of the inlet. Alternatively, megalopae could
potentially favor one side of the inlet. The larvae of 6 species of estuarine fish (Atlantic
gulf flounder, *Paralichthys albiguta*; summer flounder, *P. dentatus*; and
southern flounder, *P. lethostigma*) were more abundant on the east side of Beaufort Inlet
(Forward et al. 1999) which would result in transport towards abundant nursery habitat.
A sixth species (Atlantic croaker, *Micropagonias undulatus*) was most common in the
center of Beaufort Inlet. Our previous data suggested that blue crab postlarvae were more
abundant on the west side of Beaufort Inlet, but the study did not include all portions of
the estuary. The fourth objective of this study was to determine the relative abundance of
blue crab postlarvae entering each of the 4 major channels of the Newport River estuary and whether peaks in abundance were spatially correlated.

Materials and Methods

Seasonal Settlement

Post-larval collections were conducted at one coastal and one estuarine site near the Beaufort Inlet in the Newport River estuary, NC. The coastal site was located at Sportsman’s fishing pier on Atlantic Beach, NC approximately 4 km west of the estuary mouth. This site was moved from Triple S fishing pier, the coastal site in 2004 and 2005 (Forward 2006), because that pier was demolished. The estuarine site was the Duke University Marine Laboratory dock located approximately 3 km inside the estuary. Sampling was conducted daily from June 1 to November 15, 2006 at the estuarine site and June 1 to November 5, 2005 at the coastal site after which Sportsman’s fishing pier was also demolished.

Post-larvae were collected using cylindrical “hog’s hair” collectors similar to those described by Metcalf et al. (1995). Each 15.3 cm diameter PVC cylinder was weighted with concrete to ensure that collectors remained relatively vertical in tidal currents at the estuarine site and in waves at the coastal site. Collectors were suspended approximately 1 m below mean low water, which was near the middle of the water column during low tide at the two sites in this study. Previous studies observed no difference in the abundance of *C. sapidus* megalopae in surface and bottom samples at the estuarine site (De Vries et al. 1994). We did not directly determine differences in post-larval abundance in surface and bottom waters at the coastal site. Shanks (1998)
observed higher settlement on surface vs. bottom collectors at a coastal site near Duck, NC. Our mid-water collectors were suspended in a shorter water column and we observed post-larval abundances similar to those observed by Shanks (1998) in surface samples, suggesting that mid-water sampling provided a representative measure of megalopal abundance. Each morning, collectors were retrieved and soaked in fresh water for at least 20 min. Megalopae were then removed by spraying the collectors with fresh water and filtered using a 500 µm sieve (Metcalf et al. 1995). Post-larvae were identified using a dissecting microscope (Costlow and Bookhout 1959; Bookhout and Costlow 1977) and the total number of *Callinectes spp.* megalopae counted daily in fresh samples. Due to the high number of *Callinectes sapidus* and *Callinectes similis* in many samples, a ratio of the two local *Callinectes* species was determined by identifying 60 randomly selected individuals to species each day which was then used to calculate the abundance of *C. sapidus* postlarvae within the total number collected each day.

The number of *C. sapidus* megalopae collected in the fall at the estuarine site was compared to subsequent commercial fishery and fishery independent landings. This time period and location were used because we have similar data dating back to 1993 (Table 1). Commercial fishery data were obtained from the North Carolina Division of Marine Fisheries. Relationships were calculated after taking into account fishing effort (kg/trip) for both the local estuarine areas (Bogue Sound, Core Sound, Newport River and North River) and for the entire state. The number of megalopae collected in a given fall was compared to fishery landings 2 years later, reflecting the approximate time required for growth from the megalopa stage to crabs in the fishery (Williams, 1984). This relationship allows us to predict landings 2 years into the future (Table 2).
Postlarval settlement was related to environmental variables using time-series analysis techniques. Gaps in each settlement time series were filled in using linear interpolation and data were $\log_{10}(x+1)$ transformed to reduce the effect of large settlement peaks (Shanks 1998). Seasonal trends of increasing settlement in the early summer followed by decreasing settlement in the late fall were removed by smoothing each transformed settlement time series with a 21 day moving average, fitting the smoothed series to transformed data and calculating the residuals as in Shanks (2006). The residuals were then used for subsequent analysis. Autocorrelation analysis was used to determine the periodicity of each data set. Significance was evaluated as any value exceeding the 95% confidence interval of $\pm 2/\sqrt{N}$ where $N =$ sample size (Chatfield 1989).

For time series with significant autocorrelation, periodicity values were determined using maximum entropy spectral analysis (MESA; Levine et al. 2002). MESA uses Fourier analysis to construct a spectrum by fitting an autoregressive model to the data.

Tidal height and tidal time data were obtained from the tide prediction software Tides and Currents (Nobeltec). Tidal amplitude was calculated as the maximum difference between a low tide and subsequent high tide occurring at night. The relationship between megalopal settlement and tidal amplitude was investigated with cross-correlation analysis using lags of 0-15 days according to Wing et al. (1995). Due to significant autocorrelations for both settlement and tide time series in both years, 95% confidence intervals were calculated both assuming independent points and autocorrelation. The most conservative value was used to determine significance (Wing et al. 1995).
Wind data were obtained from the NOAA National Data Buoy Center Station 41035 (34°28’34” N 77°16’47” W) located near New River Inlet, NC. Data were also obtained for Cape Lookout, NC (Station CLKN7, 34°37’18” N 76°31’30” W), but instrument outages during most of the study period prevented use of these data. Station 41035 was chosen because the data were the most closely correlated ($r^2 = 0.63$ for wind direction; $r^2 = 0.80$ for wind speed) of several sites with the 55 days of data from Cape Lookout that were available. Original hourly data were averaged over the 24 h (diel) period starting at 07:00 h the day before collection and ending at 06:00 h on the morning of collection. This ensured that wind data corresponded to the approximate times of collector deployment. Due to the roughly east-west orientation of the shoreline at the coastal study location, wind direction was rotated 105° clockwise prior to calculating wind stress. The relationship between postlarval settlement and wind stress was investigated using cross-correlation analysis for both the cross-shore and along-shore directions.

**Evaluation of sampling duration**

During our 2004-2006 sampling effort, very low settlement was observed during much of the settlement season. The period of peak settlement was determined visually after combining data from all three years and smoothing the data with a 15-day moving average. Data were not scaled by year prior to analysis because total settlement was relatively similar for each year (8,881 – 10,909 megalopae). A 45-day period of peak settlement was identified (August 22 – October 5) and the percentage of settlement occurring before, during and after the peak period was calculated for each year. The
percentage of settlement was also calculated for extended periods of 73 days (August 8 – October 19) and 92 days (August 1 – October 31).

**Evaluation of possible sampling strategies**

Daily sampling is time consuming and may require more than one person to prevent data gaps. To determine whether sampling frequency can be reduced without introducing variability, we evaluated the effectiveness of 5 alternative sampling strategies in order of decreasing effort for personnel: A – every other day, B – every third day, C – during the week with collectors removed on weekends, D – during the week with collectors deployed on weekends, and E – once a week. For each alternative strategy, we calculated the predicted total settlement for each possible combination of sampling strategy and day of the week for the 11 years of settlement data we have collected since 1993. For example, strategy E involves sampling once a week, but there are 7 possible days for sampling each week resulting in 7 predicted settlement totals for each year (i.e. sampling only on Mondays, Tuesdays, etc.). To compare the predicted totals of each alternative strategy with observed settlement in a given year, total observed settlement was multiplied by the fraction of days sampled each week (A = 1/2, B = 1/3, C = 4/7, D = 5/7, E = 1/7) resulting in a value for total expected settlement. The % difference between total predicted and total expected settlement was then calculated and compared across strategies.
**Channel sampling**

Daily postlarval collections were conducted at one coastal and four estuarine sites near the Beaufort Inlet in the Newport River estuary, NC. The coastal site was located at Sportsman’s fishing pier on Atlantic Beach, NC approximately 4 km west of the estuary mouth. One estuarine site was located in each of the four major channels inside Beaufort Inlet which were, from west to east, Morehead Channel (Portside Marina), Radio Island Channel (Radio Island Yacht Club), Gallants Channel (Duke University Marine Lab) and Shackleford Channel (National Park Service west end dock). Sampling was conducted daily from August 14 to August 24, 2006 and September 20 to October 3, 2006. Post-larvae were collected using “hog’s hair” collectors and processed as described above for seasonal sampling.

Differences in median settlement among channels inside Beaufort Inlet were investigated using Kruskal-Wallis One Way Analysis of Variance (ANOVA) on Ranks because the data were not normally distributed nor was a normal distribution achieved using the square-root transformation (Zar, 1999). A Tukey Test was used to perform pairwise comparisons when significant differences were identified by the ANOVA (Zar, 1999). Correlation among daily samples was tested using a Spearman Rank Order Correlation (Zar, 1999) because data were not normally distributed nor was a normal distribution achieved using the square-root transformation.
Results

Magnitude and timing of settlement

Settlement of *C. sapidus* megalopae at both the coastal (Sportsman’s fishing pier) and estuarine (DUML) sites was highly episodic with periods of low settlement and occasional high settlement events (Fig. 1). At both sites, megalopal settlement remained low until mid-August, with peak settlement at the coastal site during October and periods of high settlement during early September and late October at the estuarine site. Unlike 2004-2005, when settlement at the coast was 20-27 times that of settlement in the estuary, settlement at the coastal site was only about twice that of the estuarine site in 2006. This result is likely related to the shift in sampling location from Triple S fishing pier to Sportsman’s fishing pier, which is located about 1 km further from Beaufort Inlet. Settlement was significantly autocorrelated at both sites, but was not periodic at either site. There were significant cross-correlations among sites at lags of 1 and 2 days (r = 0.19, 0.21 respectively), suggesting that, as in 2005, peaks in settlement at the coast were followed 1 to 2 days later by peaks in settlement at the estuarine site (Forward 2006).

Settlement versus environmental factors – Tidal amplitude and time

Megalopal settlement at both sites was significantly cross-correlated (p < 0.05) with amplitude of nocturnal high tide. In cross-correlation analysis, a correlation coefficient is calculated for two variables, with one fixed variable (environmental variables in this study) and a second variable that is lagged one step (day) at a time with a new correlation coefficient calculated at each lag. This analysis allowed us to investigate relationships between environmental factors and megalopal settlement on the same or
subsequent days and also allows for the detection of periodicity in the data sets when correlation coefficients alternate between positive and negative values.

At the coastal site, there were significant positive correlations at lags of 0, 1, 2 and 3 days (Fig. 2a), suggesting that settlement was high during spring tides. This is in contrast to 2004, when there was no significant cross-correlation and 2005, when high settlement was associated with neap tides. At the estuarine site, there was a significant negative correlation at a lag of 0 days and there were significant positive correlations at lags of 5, 6 and 7 days (Fig. 2b). These results are consistent with those for 2004 and 2005 (Forward 2006) and suggest a semi-lunar pattern in settlement in which high settlement occurred around the time of neap tides (day 7 after the highest amplitude tide) at the estuarine site.

*Settlement versus environmental factors – Tidal time*

Settlement at the estuarine site was relatively higher when the nocturnal high tide occurred between 01:00 – 04:00 (Fig. 3). At our study site in late summer and fall, high tide occurs in this time period during neap tides. High variability in settlement and low sample sizes prevented statistical analysis of this difference. No such trend was apparent at the coastal site (Fig. 3). These results are consistent with those for 2005, but not for 2004 when settlement at the estuarine site did not appear to be related to the time of nocturnal high tide (Forward 2006).
Settlement versus environmental factors – Wind stress

Megapoplar settlement at the coastal and estuarine sites was significantly cross-correlated with wind stress (the force winds exert on the surface of the ocean) at various lags. Cross-shore wind stress was defined such that winds from the south blowing directly through Beaufort Inlet (195°) had positive wind stress values, and along-shore winds had positive values when winds blew from the east (105°). There was a significant negative correlation between settlement at the coastal site and cross-shore wind stress at a lag of 4 days (Fig. 4a). This result suggests that peaks in settlement occurred 4 days after winds from the NE. Settlement at the coastal site was not significantly correlated with along-shore wind stress (Fig. 4b). Settlement at the estuarine site was positively correlated with cross-shore wind stress at lags of 1 and 2 days (Fig 5a), and negatively correlated at a lag of 8 days. There was no correlation with along-shore wind stress (Fig 5b). We did not observe a consistent relationship between settlement at either the coastal or the estuarine site and wind stress during the three years of this study (2004-2006).

Settlement versus blue crab landings

There is a positive linear relationship between the total number of megalopae collected in a given year and commercial landings. The relationship is not significant due to 1 outlier (1994 megalopae and 1996 landings) for NC hard crab landings (Fig. 6a) and hard crab landings in the local estuarine area (Fig. 6b) The number of crabs landed in the pot fishery generally increased as the total number of megalopae collected 2 yr earlier increased and these relationships become significant if the 1994 outlier is removed. The
preliminary data for 2006 are close to our prediction based on megalopal settlement in 2004.

**Evaluation of sampling duration**

During 3 years of postlarval sampling from June to November (2004-2006), nearly two-thirds (63.6 %) of the postlarvae were collected during a 45 day period from August 22 to October 5 (Table 3). Approximately equal percentages of postlarvae were captured prior to (18.7 %) and after (17.7 %) this period on average. The highest daily settlement occurred during this period for each of the three years. Inter-annual variability was observed in settlement around this peak period, with a higher proportion of postlarvae collected during July and early August in 2005 (26.4 %) and during October and November in 2006 (38.2). Increasing the sampling duration by 21 days (August 8 to October 19) and 40 days (August 1 to October 31) resulted in decreased inter-annual variability (Table 3).

**Evaluation of possible sampling strategies**

There was a high degree of variability for each alternative sampling strategy when total predicted settlement was compared with total observed settlement. Sampling strategy D (during the week with collectors deployed on weekends) had the lowest variability of the 5 potential sampling strategies, followed closely by sampling strategy A (every other day) (Fig. 7). By far the worst alternative sampling strategy was strategy E (once a week), for which there was as much as a 200 % difference from observed settlement.
**Megalopae in different channels of the Newport River estuary**

The spatial distribution of megalopal settlement on artificial “hog’s hair” collectors was not uniform across the four channels of the Newport River estuary. There were significant differences (p < 0.05) in settlement among the five sites (4 estuarine and 1 coastal) during both the August 14-24 (Fig. 8a) and September 20 – October 3 (Fig. 8b) sampling periods. For both sampling periods, post-hoc tests indicated a set of high settlement sites including the coastal site, Morehead channel and Gallants channel and a second set of low settlement sites in Radio Island channel and Shackleford channel. Sites within each group were indistinguishable from one another.

The timing of megalopal settlement also differed among sites during both the August and September-October sampling periods. In August, settlement was significantly correlated (p < 0.05) only for the Gallants channel and Shackleford channel sites. In September, three sites were significantly correlated (p < 0.05) including Gallants, Radio Island and Morehead channels. Settlement at the estuarine sites was never significantly correlated with settlement at the coastal site even though there was occasional correspondence between the timing of settlement peaks.

**Discussion**

Postlarval settlement at both the coastal and estuarine sites followed a seasonal pattern with low settlement in the summer and peak settlement in September and October. This pattern is similar to that observed previously for blue crabs in NC (Mense et al. 1995; Shanks et al. 1998; Forward et al. 2004; Forward 2006) and for other
estuaries on the US Atlantic and Gulf coasts (e.g. Rabalais, et al. 1995; van Montfrans et al. 1995). Our previous work in 2005 suggested that settlement at the coast was 1-2 orders of magnitude higher than in the estuary (Forward 2006). During 2006, however, the magnitude of settlement was similar at the two sites. Because the magnitude of settlement at the estuarine site was similar during 2005 and 2006, we do not think this difference was the result of a decrease in larval supply. Instead, the decrease in settlement at the coast is likely related to a shift in sampling sites from Triple S fishing pier (~3 km from Beaufort Inlet) to Sportsman’s fishing pier (~4 km from Beaufort Inlet). Our hypothesis is that larvae are entrained in an eddy that forms on the west side of Beaufort Inlet (Luettich et al. 1999) that may have been sampled from Triple S fishing pier but may not extend to Sportsman’s fishing pier and potentially was not sampled in 2006. Alternatively, some other factor such as different lighting on each pier may have contributed to the observed differences in settlement, but this would be difficult to determine because sampling was not conducted concurrently on each pier and both piers have since been demolished.

In 7 years of monitoring postlarval immigration in the Newport River estuary, Forward et al. (2004) observed maximum immigration during neap tides, when the majority of flood tide occurs at night during the fall at the study site. The authors speculated that flood tide transport (FTT) behaviors, during which megalopae swim up into the water column during night-time flood tides and remain on the bottom at all other times, were the cause of this neap tide pattern in settlement. A possible alternative is that arrival at the coast could be highest during neap tides and the pattern observed in the estuary is simply the result of processes occurring offshore. Our 2005 data suggested that
high settlement was correlated with low tidal amplitude (neap tides) at both the coastal and estuarine sites suggesting that the latter explanation might be possible. However, periodicity in the correlation between settlement and tides at the coastal site (~20 days) did not match the expected periodicity for a tidal rhythm in settlement, whereas the correct periodicity was observed at the estuarine site (~14 days). This result suggested that FTT transport was more likely to be involved in determining the pattern of settlement at the estuarine site. In 2006, high settlement at the coastal site was associated with maximum tidal amplitude (spring tides), whereas high settlement at the estuarine site was associated with minimum tidal amplitude (neap tides). Taken together, these data confirm that Forward et al. (2004) were correct in speculating that postlarval immigration into the Newport River estuary is largely regulated by FTT behaviors and is only weakly related to abundance outside the estuary as determined by settlement on artificial collectors. Settlement at the coast is clearly not controlled by FTT, but must be the result of some other combination of behavior and oceanographic processes.

Identifying the mechanisms of postlarval transport from offshore developmental areas to the coast has been difficult because potential transport mechanisms are more numerous and sufficient behavioral data are lacking. Transport of blue crab postlarvae to the US Atlantic coast is thought to be primarily the result of wind driven Ekman currents, in which larvae at the surface would be advected toward the coast during winds from the northeast (Epifanio and Garvine 2001). In this case, we would expect high settlement events at the coast during or soon (1-2 days) after strong northeast winds. Advection to the coast may also occur during relaxation of upwelling fronts (Shanks et al. 2000), in which case we might observe high settlement 1-2 days following strong southeast winds.
Finally, transport could occur in internal tidal bores (Vargas et al. 2004) or potentially in surface convergence zones over internal waves (Shanks 1983; Shanks 1988). Internal waves can be generated along the continental shelf break during maximum amplitude tides (see Shanks 2006 for review of mechanisms). Larval transport by internal waves would result in a semilunar settlement pattern but would not necessarily be associated with any particular phase of the tide because wave speed is determined by stratification and other physical properties of the water column (Shanks 2006).

During the 2004-2006 sampling seasons, we did not observe any consistent relationships between postlarval settlement at the coast and environmental variables. There were significant negative correlations with cross-shore wind stress during each year, suggesting high settlement associated with northeast winds, but at lags of 0 days in 2004, 10 days in 2005 and 4 days in 2006. These results do not suggest a strong correlation between wind and coastal abundance. One difficulty was that southerly wind events often generated strong waves that prevented sampling, possibly obscuring any relationship between settlement and wind stress.

Significant correlations between tidal amplitude and settlement were observed in 2 of the 3 years, but were different among years. In 2005, settlement was negatively correlated with tidal amplitude at lags of 0-3 days and positively correlated at lags of 8-12 days. In 2006 the pattern reversed with positive correlations at lags of 0-3 days and negative (but non-significant) correlations at 9-11 days. Although these results suggest a potential link between tides and settlement at the coast, the period of the correlogram is not semilunar as was observed for all three years at the estuarine site. Thus, it is not clear from these results that either wind- or tide-driven transport processes played a dominant role.
role in driving advection of blue crab postlarvae to the coast from offshore developmental areas. Detailed mechanistic experiments are needed to evaluate hypotheses concerning advection of postlarvae to the coast.

One of the fundamental goals of fisheries management is to predict the future yield of a given fishery based on larval or juvenile abundance. To date, scientists and managers have been largely unsuccessful in predicting the future yield of the blue crab fishery in NC and elsewhere (NC - Eggleston et al. 2004; Chesapeake Bay – Lipcius and Stockhausen 2002). In the stock assessment associated with the 2004 NC Blue Crab Management Plan, Eggleston et al. (2004) found stronger correlations between age 0 (juvenile) and age 1 (adult) crabs within a given year rather than with a 1 year lag that would be expected given what is known of blue crab growth rates. Our previous studies (Forward et al. 2004; Forward 2006) found a highly significant relationship (with 1 outlier) between postlarval immigration and fishery landings (CPUE) statewide and in the local estuarine region, with the adult abundance survey (Program 195, CPUE) and with the juvenile abundance survey (Program 120, CPUE; no outliers). This study lengthens the data set to 9 years, for which there remains a highly significant relationship between NC statewide landings and postlarval settlement. Additional data are currently being analyzed to update correlations with the fishery independent surveys.

One criticism of this relationship is that a measurement of immigration at a single location is unlikely to accurately measure immigration at a variety of locations statewide. Blue crab postlarval immigration is a highly episodic process that likely depends on local conditions. Within a given year, no relationships in the timing of settlement events among sites have been observed over large geographic regions (van Montfrans et al.
1995; Rabalais et al. 1995), with the exception of sites within a single estuary (Rabalais et al. 1995). To more accurately assess postlarval recruitment to the Albemarle-Pamlico estuarine system, sampling should be carried out at additional sites near Ocracoke or Hatteras Inlets and at Oregon Inlet.

To minimize the cost and effort of a sustained or expanded blue crab postlarval immigration monitoring program, we assessed the optimal timing and duration of sampling and identified the most effective of several potential sampling strategies. Over a 3-year period (2004-2006), nearly two-thirds of the settlement occurred during a 45-day window from August 22 to October 5 (Table 3). Given that there was significant inter-annual variability in this number (45.5 % to 69.7 %), we recommend an optimal sampling period from August 1 to October 31. This longer period encompassed 85 % of the total settlement (Table 1) with low inter-annual variability (82.1 % to 88.1 %).

Although we considered a variety of alternative sampling strategies, daily sampling is by far the most effective strategy for determining the annual immigration of blue crab postlarvae. Of the alternative strategies tested, sampling 5 consecutive weekdays (leaving collectors in the water over the weekend) was slightly less variable than sampling every other day with a similar level of effort. Sampling one day a week was a very poor measure of annual immigration. Even for the best alternative strategy (5 consecutive weekdays), we would expect estimates to deviate by >20 % approximately 1 out of every 10 years. Put another way, for a year with moderate settlement (~ 7000 total megalopae), this strategy could result in estimates ranging from 5600 to 8400. Thus, we recommend daily sampling as the only effective method for estimating annual immigration.
Blue crab postlarval immigration was not evenly distributed across the Newport River estuary. Instead, postlarvae were preferentially collected in the three western channels (Morehead channel, Radio Island channel, Gallants channel), but rarely in Shackleford Channel. This result was surprising because previous studies in Beaufort Inlet observed higher numbers in Shackleford channel for 6 of 7 species of fish larvae (Forward et al. 1999). The authors hypothesized that the location of entry into the estuary reflected the location of the source population offshore. The distribution of blue crab postlarvae we observed may also reflect the location of the larval source or part of the eddy they accumulate in. Alternatively, postlarvae could select the estuarine water mass along the western side of the inlet as they are known to respond to estuarine chemical cues (e.g. Forward et al. 1996).

Although some significant correlations among sites were observed, these correlations were not strong or consistent among sampling periods. Short-term variability among sites could be due to a patchy distribution of postlarvae entering Beaufort Inlet. In Delaware Bay, Jones and Epifanio (2005) observed patches of C. sapidus megalopae on the scale of 500 – 2000 m radius. Alternatively, these results could suggest that settlement is very site-dependent or affected by factors operating on small spatial scales such as wind forced changes in tidal flow (Logan et al. 2000, Churchill et al. 1999). Although we sampled during the expected time of peak settlement, we were unable to capture a peak settlement event (when settlement increases by 1-2 orders of magnitude for a day or more). It would be interesting to determine if peak settlement events occur simultaneously across the estuary, indicating the presence of a larger patch of megalopae, or whether they too are variable across sites.
Summary Statement

Postlarval settlement of the blue crab near the Newport River estuary, NC increased during the late summer to a peak from late August to early October. Settlement was highly episodic with typically low levels of settlement punctuated by several major settlement events each year. Flood tide transport was the primary mechanism of entry into the estuary, with some pulses of immigration associated with onshore wind events. Settlement on artificial collectors inside the estuary was rarely related to settlement on the coast, suggesting a weak relationship between postlarval supply and immigration. There was a strong spatial component to postlarval immigration, with high settlement restricted to the three western sub-estuaries of the Newport River estuarine system and little temporal correlation among sampling locations. There remains a significant relationship (with one outlier) between postlarval immigration and statewide fishery landings. A continued or expanded postlarval monitoring program should include daily sampling over a three-month period from August 1 to October 31.
References


distribution of larvae of *Callinectes sapidus* (Crustacea: Decapoda) in the waters adjacent to Chesapeake Bay. Journal of Crustacean Biology 3: 582-591.


Shanks, A.L. 2006. Mechanisms of cross-shelf transport of crab megalopae inferred from


Williams, A.B. 1984. Shrimps, lobsters and crabs of the Atlantic coast of the eastern United States, Maine to Florida. Smithsonian Institutional Press, Washington, D.C.


Table 1. Collection periods at the Duke University Marine Laboratory (DUML) dock, total megalopae collected and number of megalopae in the 6 largest peaks each year.

<table>
<thead>
<tr>
<th>Yearly Starting Dates</th>
<th>Collection Period Duration</th>
<th>Nights not Sampled</th>
<th>Total Megalopae Collected</th>
<th>Number in 6 Largest Peaks</th>
<th>Percent of Total in 6 Largest Peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/15/1993</td>
<td>69 nights</td>
<td>8</td>
<td>2,190</td>
<td>1,369</td>
<td>63.5%</td>
</tr>
<tr>
<td>9/6/1994</td>
<td>71 nights</td>
<td>6</td>
<td>4,457</td>
<td>2,055</td>
<td>46.1%</td>
</tr>
<tr>
<td>9/13/1995</td>
<td>69 nights</td>
<td>0</td>
<td>9,229</td>
<td>5,038</td>
<td>54.6%</td>
</tr>
<tr>
<td>9/14/1996</td>
<td>70 nights</td>
<td>4</td>
<td>12,007</td>
<td>8,086</td>
<td>67.3%</td>
</tr>
<tr>
<td>9/11/1998</td>
<td>76 nights</td>
<td>4</td>
<td>2,259</td>
<td>734</td>
<td>32.5%</td>
</tr>
<tr>
<td>9/2/2000</td>
<td>73 nights</td>
<td>0</td>
<td>5,273</td>
<td>3,400</td>
<td>64.5%</td>
</tr>
<tr>
<td>9/1/2002</td>
<td>63 nights</td>
<td>3</td>
<td>1869</td>
<td>1007</td>
<td>53.9%</td>
</tr>
<tr>
<td>8/28/2003</td>
<td>87 nights</td>
<td>9</td>
<td>5349</td>
<td>4176</td>
<td>78.1%</td>
</tr>
<tr>
<td>9/1/2004</td>
<td>76 nights</td>
<td>0</td>
<td>8197</td>
<td>2569</td>
<td>31.3%</td>
</tr>
<tr>
<td>9/1/2005</td>
<td>76 nights</td>
<td>0</td>
<td>6358</td>
<td>4415</td>
<td>69.4%</td>
</tr>
<tr>
<td>9/1/2006</td>
<td>76 nights</td>
<td>11</td>
<td>5937</td>
<td>2204</td>
<td>37.1%</td>
</tr>
</tbody>
</table>

Table 2. Predicted Blue Crab harvest for future years in the local estuary (Bogue Sound, Core Sound, Newport River, North River) and all of North Carolina based upon megalopal catch at DUML from 2005-2006 (Table 1) and equations from Figure 6.

<table>
<thead>
<tr>
<th>Year</th>
<th>Local estuary (Kg/trip)</th>
<th>North Carolina (Kg/trip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>181</td>
<td>214</td>
</tr>
<tr>
<td>2008</td>
<td>179</td>
<td>212</td>
</tr>
</tbody>
</table>
Table 3. Percent of the yearly total number of megalopae collected during 5 sampling periods from 2004 to 2006. Average percent settlement is calculated for all three years combined.

<table>
<thead>
<tr>
<th>Sampling Period</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/9-8/21</td>
<td>12.5</td>
<td>26.4</td>
<td>16.3</td>
<td>18.7</td>
</tr>
<tr>
<td>8/22-10/5</td>
<td>72.9</td>
<td>69.7</td>
<td>45.5</td>
<td>63.6</td>
</tr>
<tr>
<td>10/6-11/8</td>
<td>14.6</td>
<td>3.9</td>
<td>38.2</td>
<td>17.7</td>
</tr>
<tr>
<td>8/8-10/19</td>
<td>85.1</td>
<td>79.6</td>
<td>67.7</td>
<td>77.9</td>
</tr>
<tr>
<td>8/1-10/31</td>
<td>88.1</td>
<td>82.1</td>
<td>86.8</td>
<td>85.5</td>
</tr>
</tbody>
</table>
Figure 1. Settlement of *C. sapidus* megalopae at a coastal (Sportsman’s fishing pier) and estuarine (DUML) site during summer and fall 2006.
Figure 2. Cross-correlation between megalopal settlement and amplitude of nocturnal flood tide at the coastal site (a) and estuarine site (b). Dotted lines indicate 95% confidence intervals. Day zero is the time of maximum amplitude high tide (spring tides).
Figure 3. Mean number of megalopae per collector vs. time of nocturnal high tide.
Figure 4. Cross-correlation between settlement at the coastal site and cross-shore wind stress (a) and along shore wind stress (b). Dotted lines indicate 95% confidence intervals.

a)

b)
Figure 5. Cross-correlation between settlement at the estuarine site and a) cross-shore wind stress and b) along-shore wind stress. Dotted lines indicate 95% confidence intervals.

a) 

Correlation coefficient (r)  
Lag (days)  
-16 -14 -12 -10 -8 -6 -4 -2 0

b) 

Correlation coefficient (r)  
Lag (days)  
-16 -14 -12 -10 -8 -6 -4 -2 0
Figure 6. Relationship between megalopa settlement at the DUML site and NC landings (kg/trip) (a), and landings in the local estuary (Bogue Sound, Core Sound, Newport River and North River/Back Sound (b). Dotted lines indicate 95% confidence intervals. The value of $r^2$ is reported for the relationship without the outlier (1994).

a)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6a.png}
\caption{Total Megalopae Collected at DUML vs. NC Landings (kg/trip).}
\end{figure}

$r^2 = 0.711$

b)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6b.png}
\caption{Total Megalopae Collected at DUML vs. Hard Crab Landings (kg/trip).}
\end{figure}

$r^2 = 0.270$
Figure 7. Box plot of residuals for sampling strategies A (every other day; n = 22), B (every third day; n = 33), C (during the week with no sampling on weekends; n = 77), D (during the week with collectors deployed on weekends; n = 77) and E (once a week; n = 77). Values on the y-axis represent the % difference from total observed settlement for the total of each simulated settlement time series. The shaded area represents the spread of 75 % of data around the median, whiskers represent 90 % of data around the median and triangles represent individual data points for the top and bottom 5 % of data.
Figure 7. Megalopal settlement at the coast (Sportsman’s Pier) and 4 channels in the Newport River estuary during (a) August and (b) September – October.

a)

b)