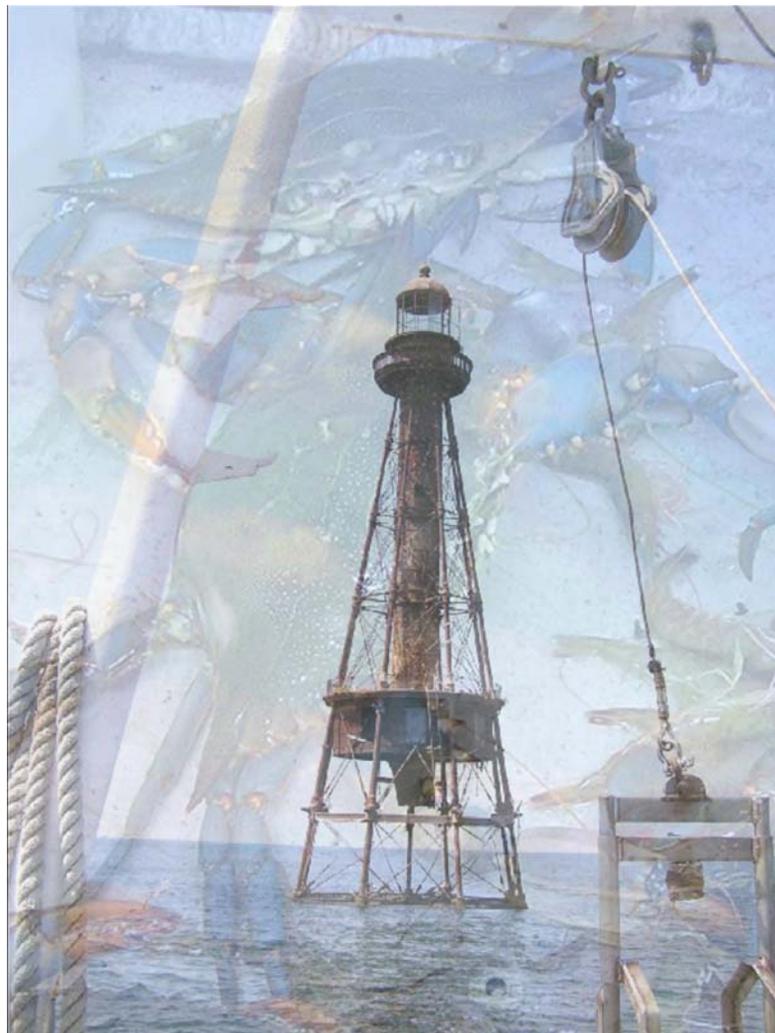




Coastal Marine Institute

Blue Crab (*Callinectes sapidus*) Use of the Ship/Trinity/Tiger Shoal Complex as a Nationally Important Spawning/Hatching/Foraging Ground

Discovery, Evaluation, and Sand Mining Recommendations Based on Blue Crab, Shrimp, and Spotted Seatrout Findings



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Authors

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December 2010

Prepared under MMS Contract
1435-01-04-CA-32806-35161 (M05AZ10660)
by
Louisiana State University
Department of Oceanography and Coastal Sciences
School of the Coast and Environment
Baton Rouge, Louisiana 70803

Published by

**U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region**

**Cooperative Agreement
Coastal Marine Institute
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CITATION

Condrey, R.E. and C.G. Gelpi. 2010. Blue crab (*Callinectes sapidus*) use of the Ship/Trinity/Tiger Shoal Complex as a nationally important spawning/hatching/foraging ground: Discovery, evaluation, and sand mining recommendations based on blue crab, shrimp, and spotted seatrout findings. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2009-043. 42pp.

ABOUT THE COVER

Blue crab catch overlaying a view of the Ship Shoal Lighthouse taken by the authors from the stern of the RV *Pelican*.

ACKNOWLEDGMENTS

Funding for this project was provided by MMS through Cooperative Agreement No. 1435-01-04-CA-32806, Task Order 35161 (Ship Shoal: Sand, Shrimp, and Spotted Seatrout), LSU Proposal No. 16626, as part of the LSU/MMS Coastal Marine Institute. This study was conducted in conjunction with a larger effort to understand the sand-mining ecology of Ship Shoal and the Ship/Trinity/Tiger Shoal Complex (e.g., Stone et al. 2009). Since these larger projects contained funds for shrimp-directed, fishery independent trawls of the study areas, the present study was closely coupled with the two larger studies and this report has also been included as Chapter 12 of final report for the larger Ship Shoal study (Stone et al. 2009). We would like to thank MMS for providing us the flexibility to fully pursue this multi-disciplinary research in cooperation with Dr. Greg Stone, Dr. John Fleeger, Dr. Stanislas Dubois, Mark Grippo, Elaine Evers, Sara Arndt, Marjo Alavillamo, Francois Reynal, Dr. Felix Jose, Dr. Baozhu Li, Dr. Daijiro Kobashi, and Syed M. Khalil.

During our study, we greatly benefited from the advice provided by the Louisiana Sand Management Working Group and the Coastal Ecology Group of the Louisiana Department of Wildlife and Fisheries. We are indebted to the captains and crew of Louisiana Universities Marine Consortium's RV *Acadiana* and RV *Pelican* for the extraordinary part they played in making each biological sampling trip a success.

Dr. J. Geaghan provided valuable statistical advice. Dr. D. B. Eggleston provided us with a prepublication copy of Eggleston et al. (in review) and Dr. R. M. Overstreet with an early draft of Shields and Overstreet (2007). S. Wells in Dr. J. R. McConaughy's lab provided valuable insight on procedures for estimating number of eggs in a blue crab sponge. Dr. T. Wolcott, S. Wells, and Gerald Adkins provided valuable reviews of our blue crab manuscript.

We benefited from blue crabs discussions with Dr. M. Ogburn, Dr. R. A. Tankersley, D. L. Dudley, Harriet Perry, and Vince Guillory.

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ABBREVIATIONS

AH	abdominal hairs located on the pleopods of a female blue crab
ANCOVA	analysis of covariance
ANOVA	analysis of variance
BACI	before-after, control-impact
BB	blue crab carapace width at the base of lateral spines
BC	acorn barnacle exoskeleton coverage of a blue crab
BW	acorn barnacle weight on a blue crab
C	blue crab body weight without tail
D	largest acorn barnacle diameter on a blue crab
E	number of eggs in a blue crab sponge
G	gooseneck barnacle intensity on blue crab gills
GN	presence/absence of nemerteans on blue crab gills
H	blue crab carapace height
L	blue crab carapace length
O	blue crab ovary fullness on a three-point scale
O _{sc}	ovarian condition as a function of blue crab sponge color
P	presence or absence of a sponge on a mature female blue crab
R ²	residual sum of squares
S	blue crab spermathecae
SC	blue crab sponge color
SEAMAP	Southeast Area Monitoring and Assessment Program
SN	nemertean intensity on blue crab sponge
STTSC	Ship/Trinity/Tiger Shoal Complex
t	time
T	blue crab tail weight
TT	blue crab carapace width between the lateral spines
V	volume
W	blue crab weight without acorn barnacles
X	linear estimate of volume

EXECUTIVE SUMMARY

The Minerals Management Service (MMS) is addressing the recent demand for long-term use of U.S. continental shelf sand resources for coastal erosion management, a critical challenge to Louisiana's ecosystems and economies (e.g., USDOJ, MMS 2008). Louisiana considers barrier island restoration as a promising way to combat wetland loss with sand mined from Ship Shoal, located off the central Louisiana coast, as the most feasible sediment source. Additional resources on the nearby Trinity and Tiger Shoals are also being considered.

These shoals and the surrounding area support major shrimp fisheries. During our shrimp-directed trawling efforts, we failed to find abundance concentrations of shrimp on these shoals, but found unexpected and persistent concentrations of healthy spawning, hatching, and foraging female blue crabs.

At the conclusion of our study we were able to conclude that Ship and Trinity Shoals and much of the surrounding area form an important offshore spawning/hatching/foraging ground for a large segment of the Gulf of Mexico blue crab fishery from at least April – October. During this time, mature female blue crabs appear to be in a continuous spawning cycle, producing new broods approximately every 21 days while actively foraging on the Shoal to supply the necessary energy for this continuous reproductive activity. Egg production apparently declines slightly as the season progresses, perhaps reflecting some ingestion-limited growth of the ovary as infaunal prey densities on the Shoal decline. Despite the Shoal's comparatively higher salinities, Ship Shoal's crabs are as fecund and 'meaty' as those from any known U.S. blue-crab spawning ground. Sand mining on the Shoal is expected to result in some decline in blue crab fecundity and condition factor through a reduction in food supply. In addition, increases in suspended sediments associated with sand mining may increase the mortality of crab larvae. Sand mining practices which minimize these potentially negative impacts should be carefully considered, along with regulations which will protect the contribution these crabs make to the stability of Louisiana's traditional inshore fishery.

INTRODUCTION

OVERVIEW

The Minerals Management Service (MMS) is addressing the recent demand for long-term use of U.S. continental shelf sand resources for coastal erosion management, a critical challenge to Louisiana's ecosystems and economies (e.g., USDOJ, MMS 2008). Louisiana considers barrier island restoration as a promising way to combat wetland loss with sand mined from Ship Shoal, located off the central Louisiana coast (Figure 1), as the most feasible sediment source. Additional resources on the nearby Trinity and Tiger Shoals (Figure 1) are also being considered.

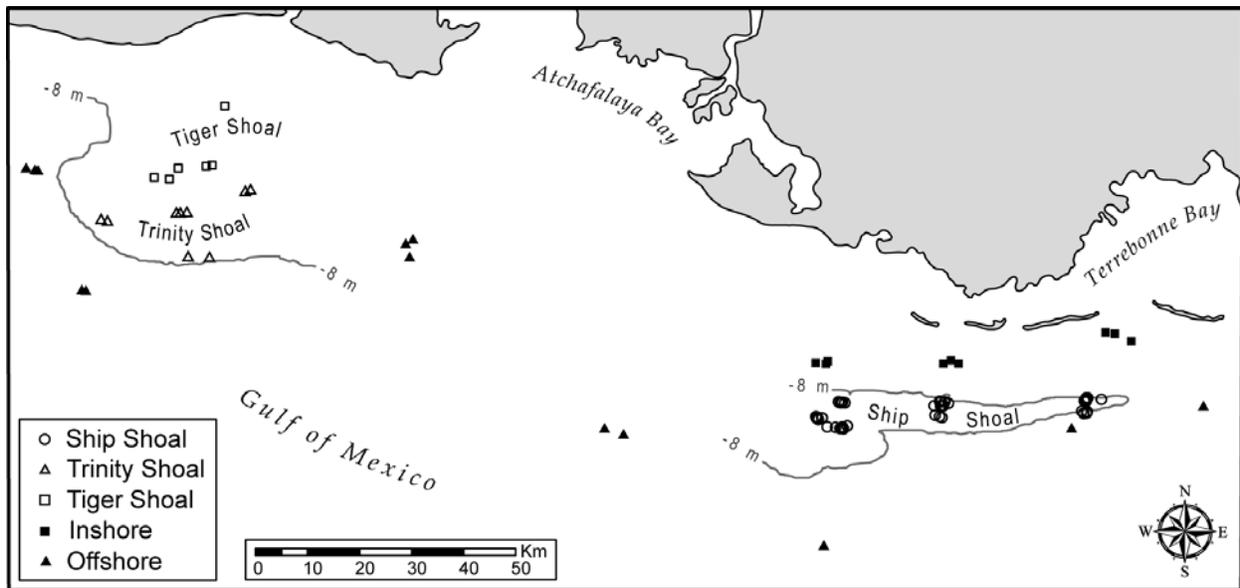


Figure 1. Ship/Trinity/Tiger Shoal Complex (STTSC) and trawl station locations for 2005-2007. Areas within the STTSC are divided into five groups (see key). Ship, Trinity, and Tiger Shoals are partly outlined by the 8 m contour associated with each shoal (based on Braud 1999).

Together Ship, Trinity, and Tiger Shoal and the surrounding waters can be considered the Ship/Trinity/Tiger Shoal Complex (STTSC, Figure 1). The STTSC supports major demersal fisheries on white and brown shrimp (*Litopenaeus setiferus* and *Farfantepenaeus aztecus*), species which are major components of the STTSC ecosystem. Given the national importance of these fisheries and the constraints in which they operate, negative impacts of sand mining on these directed fisheries would have far reaching implications. The present study was conducted as part of a larger effort to understand the sand-mining ecology of Ship Shoal and the STTSC (e.g., Stone et al. 2009). Since these larger projects contained funds for shrimp-directed, fishery independent trawls of the study areas, the present study was closely coupled with the two larger studies.

During our shrimp-directed trawling efforts, we found unexpected and persistent concentrations of spawning, hatching, and foraging female blue crabs (*Callinectes sapidus*) in the STTSC, first on Ship Shoal in 2005 and 2006 and then on the STTSC in 2007 when MMS funding allowed a broadening of our study area. Almost all of our crabs were healthy, mature females involved in foraging and brood production/care (Figure 2). One mature female was soft-shelled and had

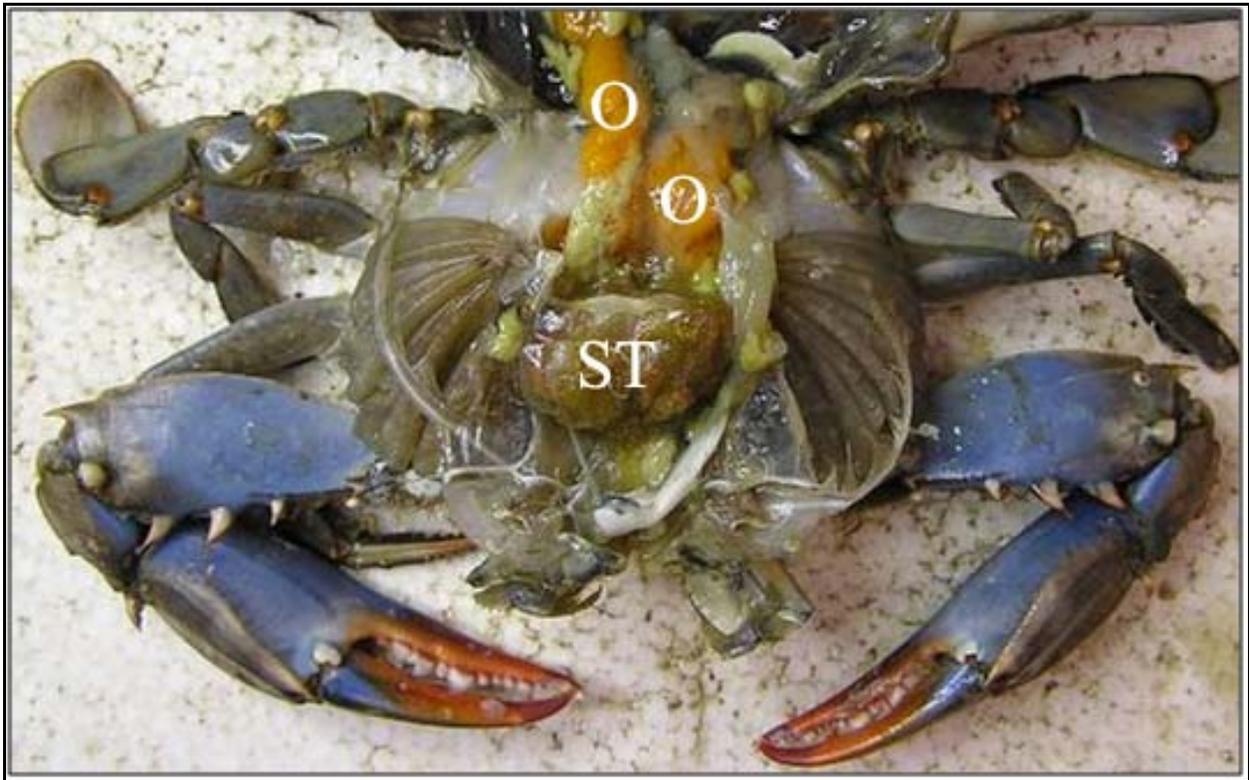


Figure 2. Interior view of a nonovigerous blue crab, which had hatched empty egg casings, from the Ship/Trinity/Tiger Shoal Complex. The full stomach (ST), full ovary (O), and egg casings (not shown) suggest that this crab was actively foraging while preparing to spawn again.

recently mated, and two other mature females showed signs of recent mating. At the same time, we found little evidence that white or brown shrimp, or their economically and ecologically important predator spotted seatrout (*Cynoscion nebulosus*), were abundant on the surface of Ship, Trinity, or Tiger Shoal.

Given these dual findings, the focus of the present study shifted from an analysis of the potential impacts of sand mining on the abundance and condition factor/fecundity of shrimp to spawning blue crabs. Blue crabs are an ecologically important crustacean which supports the world's most valuable crab fishery, despite recent reports of regional overfishing. Louisiana currently leads all other U.S. states in blue crab landings.

Our study represents at least five blue crab firsts. It is the first time analysis of covariance (ANCOVA) and multiple regression analyses have been used to assess multiple indicators of condition factor and reproductive vigor of mature female blue crabs within and across spawning

areas; the first documentation of an extensive blue crab spawning/hatching/foraging ground in offshore waters; the first indication that mating of blue crabs is not limited to estuarine conditions; the first indication that the nemertean *Carcinonemertes carcinophila* may have an observable effect on blue crab health or weight; and the first statistical suggestion that prey reduction through crab predation has resulted in a decline in crab fecundity. In addition we present evidence that the STTSC crabs are in a continuous spawning cycle from at least April through October and that the currently used index of blue crab size (width of the carapace across the lateral spines) should be replaced with better indicators of overall size and volume.

For the purpose of evaluating the potential impacts of sand mining, we develop and test a series of regression, multiple regression, ANCOVA, and analysis of variance (ANOVA) approaches which can be used in a BACI to monitor the impact of sand mining on the abundance, condition factor, and reproductive vigor of mature female blue crabs. While all of our approaches proved meaningful, our density-related results are the least sensitive, though our fishery-independent catch statistics are comparable to other studies of blue crab abundance across the U.S. Our results are most sensitive to changes in blue crab condition factor and reproductive vigor, making us confident that this portion of our overall approach would detect any meaningful adverse impacts of the limited sand mining currently being considered by MMS for Ship Shoal. We recommend an enhancement of both approaches for use in an ecologically-based monitoring of the potential impacts of sand mining operations on this newly discovered, and nationally important, blue crab spawning/hatching/foraging ground.

ORIGINAL PROJECT SCOPE AND REASONS FOR PROJECT REVISION

Our original intention for this project was to study how the population dynamics of three recreationally, commercially, and ecologically important species – white shrimp, spotted seatrout, and brown shrimp--on Ship Shoal might be affected by sand mining. Particular emphasis was to be paid to white shrimp, given their historic use of the area and importance as a spotted seatrout prey. Shrimp were to be collected by participating in the onshoal cruises conducted as a part of Stone et al. (2009) and offshoal cruises conducted by the Louisiana Department of Wildlife and Fisheries (e.g., Hanifen 2008). Samples of seatrout were to be collected from recreational fishers who frequented Ship Shoal and its surrounding waters. Multiple regression and ANCOVA models relating relevant life history features to environmental conditions were to be developed and used in a BACI analysis of the impacts of sand mining on the three species of concern.

The six questions we were to address were:

1. Are white and/or brown shrimp populations more concentrated at Ship Shoal as compared to non-shoal areas?
2. Are spotted seatrout and Atlantic croaker populations more concentrated at Ship Shoal as compared to non-shoal areas?

3. Does the sex ratio, stage of maturation, mean size, and/or condition factor of these fishery resources differ between Ship Shoal and non-shoal areas independent of the effects of season, water depth, and/or year?
4. What are the dominant prey species found in the guts of these organisms?
5. Are the gut content patterns of these four fishery resources different between Ship Shoal and non-shoal areas? If so, do these differences reflect known prey preferences for sandy substrate?
6. Are non-shoal areas likely to serve as alternative foraging and maturing habitats for these four fishery resources during periods of sand removal from Ship Shoal and/or during recolonization of and removal sites?

During the initial phase of this project, we found little evidence for direct, persistent use of Ship Shoal by white or brown shrimp or regular recreational use of Ship Shoal by recreational fishers. At the same time, under separate MMS funding (Stone et al. 2009) we found unexpected concentrations of female blue crabs apparently using Ship Shoal as a spawning, hatching, and foraging ground. As time progressed, it became apparent that the surface of Ship Shoal is not currently an important white shrimp habitat in terms of fishery independent catch or commercial fishing effort. At the same time, it became equally apparent that not only Ship Shoal, but Trinity Shoal and (to a lesser extent) the entire STTSC, are important spawning, hatching, and foraging grounds for blue crabs. Therefore, we began applying and expanding the types of measurements we had intended for our shrimp-related BACI to our catches of blue crabs.

REVIEW OF THE RELEVANT BLUE CRAB LITERATURE

This review relies heavily on the current synthesis provided in Kennedy and Cronin (2007). Additional references are included as appropriate.

Blue crabs are an ecologically and economically important crustacean, historically common along the U.S. Atlantic and Gulf of Mexico coasts. Blue crab supports the most valuable crab fishery in the world (Eggleston et al. 2008). The U.S. fishery accounted for 87% of the world blue crab catch in 1999 (UN 2008). Within the United States, Louisiana leads all other states in recent (1997-2006) hard-shelled landings (26% of the U.S. total), followed by North Carolina (22%), the Chesapeake Bay states of Maryland and Virginia (31%, combined) and the remaining thirteen blue-crab producing states (Rhode Island to Texas, 21%, combined) (USDOC, NOAA 2007).

Louisiana's recent dominance in U.S. blue crab landings is largely attributable to 1) increases in Louisiana's yield and 2) recent declines in the blue crab fisheries of Chesapeake Bay, Maryland and Virginia, North Carolina, and other states (statistics in USDOC, NOAA 2007). The Chesapeake and North Carolina declines are attributed to overfishing and habitat degradation. As a result, management in these areas are considering/implementing methods of increasing spawning stock biomass through regulations (i.e., migration corridors and spawning sanctuaries) augmented by an experimental release of hatchery-raised juveniles (Aguilar et al. 2008; Eggleston et al. 2008).

Major features of the blue crab life cycle include 1) a single, life-time mating event for the female; 2) a salinity-associated separation of the sexes following mating; 3) post-fertilization care of young by the ovigerous (in-berry) female; 4) hatching in continental-shelf associated waters; and 5) estuarine development of juveniles (Churchill 1919; Van Engel 1958).

Mating is expected to occur when the female is undergoing her terminal molt (Churchill 1919) and involves a soft-shelled female and hard-shelled male. A hard-shelled adult female is not expected to mate. Until the present study, mating has only been reported from estuarine systems. A female may mate with more than one male during her terminal molt, however a single-partner mating is expected for most females. Sperm are transferred in spermatophores and stored in the female's spermathecae. The spermathecae of newly mated females are filled with a hardened seminal fluid, which begins to soften and disappear over a period of perhaps two months (Hard 1945; Wolcott et al. 2005).

After the terminal molt, the ovary begins to develop mature eggs. During spawning, eggs are released into the female's spermathecae and fertilized with a portion of the stored sperm. It is expected that the sperm to egg ratio required for fertilization is greater than 1:1. The possibility that the concentration/viability of stored sperm may artificially limit fertilization is of concern in areas where males are intensely harvested (Hines et al. 2003; Carver et al. 2005).

Once released from the female's body cavity, the eggs attach to the females' swimmerets (Churchill 1919). The presence of sediment may be necessary for egg attachment (Schaffner and Diaz 1988). The attached egg mass is commonly referred to as a 'sponge'. As the fertile eggs develop, proliferation of pigments in the embryo change the color of the sponge from bright orange (newly released) to black (ready to hatch) within a period of about fifteen days.

Tagging and tracking studies suggest that spawning along the U.S. Atlantic and central/western Gulf occurs within the lower estuary or just outside the estuary (Tagatz 1968; More 1969; Carr et al. 2004). Since egg development and hatching success are apparently enhanced by salinities of at least 20 ppt (Sandoz and Rogers 1944; Davis 1965), seaward movement of estuarine-based, pre-hatching females is expected to enhance larval success, though parasitism, disease, and fouling of adult females is expected to increase with salinity (Shields and Overstreet 2007). There is evidence suggesting that some females will migrate back into less saline estuarine waters between hatchings to forage (Daugherty 1952; Tankersley et al. 1998), while others may continue to move seaward for successive spawns (Hench et al. 2004; Forward et al. 2005). Published gut content and stable isotope studies of spawning/hatching crabs are lacking.

Tagging studies on the west coast of Florida suggest an interesting variation on the movement of post-mating/pre-spawning females (i.e., Steele 1991). Here some females may spawn near their mating estuary while other females migrate long distances along the coast before spawning.

Mature females may have more than seven broods per spawning season (Dickinson et al. 2006) and live to spawn in multiple seasons. After hatching, remnants of old, empty egg cases remain attached to the swimmerets of the mother crab for an unknown period (Churchill 1919).

There are a limited number of equations describing various aspects of the population dynamics of mature female blue crabs. These include width-weight equations for nonovigerous female blue crabs (Newcombe et al. 1949; Pullen and Trent 1970; Hines 1982; Olmi and Bishop 1983; Rothschild et al. 1992; modified from H. Perry in Guillory et al. 2001, Figure 3.5; Lipcius and Stockhausen 2002). The statistical similarities of these equations have not been tested. In addition there are two published studies relating fecundity to either dry body weight or size (Hines 1982; Prager et al. 1990). The statistical similarities of these equations have not been tested. Dickinson et al. (2006) provides four, clutch-specific equations relating sponge volume to width which suggest a decline in sponge volume with clutch number. Reasons for this decline were not explored, but may relate to crab culture in minnow traps.

BLUE CRAB OBSERVATIONS LEADING TO REVISED PROJECT HYPOTHESES

We found unexpected and persistent concentrations of spawning, hatching, and foraging female blue crabs off the Louisiana coast in 2005 to 2007, first on Ship Shoal in 2005 and 2006 and then on the STTSC in 2007 when MMS funding allowed a broadening of our study area. Of the 516 crabs, 511 were mature females, four were mature males, and one was an immature male. The vast majority of mature females (90%) were either in-berry (Figure 3) or/and contained full gonads (Figure 4c). The majority of nonovigerous females had hatched egg casings on their abdomens (Figure 5) and full ovaries (C in Figure 4) suggesting that they were preparing for an additional spawn. While many of our crabs contained acorn barnacles (*Chelonibia patula* Ranzani and Balanus spp.; Shields and Overstreet 2007) on the exoskeleton, the gooseneck barnacle *Octolasmis muelleri* (Coker; Shields and Overstreet 2007) on their gills, and/or the nemertean *Carcinonemertes carcinophila* (Kölliker; Shields and Overstreet 2007) in their gills and/or sponges, almost all appeared healthy (Figure 6).

We also found the first reported evidence of the offshore mating of blue crabs. One mature female was undergoing her terminal molt (adult abdomen, incompletely calcified exoskeleton, top and middle panels of Figure 7) and had enlarged spermathecae which were consistent with Jivoff et al. (2007)'s description of a female blue crab which had just copulated (bottom panel of Figure 7).

In addition to the female in Figure 7, we found two other female blue crabs within the STTSC which had evidence of recent mating but hardened exoskeletons (Figure 8). Virtually all of the remainder of our female blue crabs examined had resorbed spermathecae (Figure 9), characteristic of post-mating ovarian development in preparation for spawning.

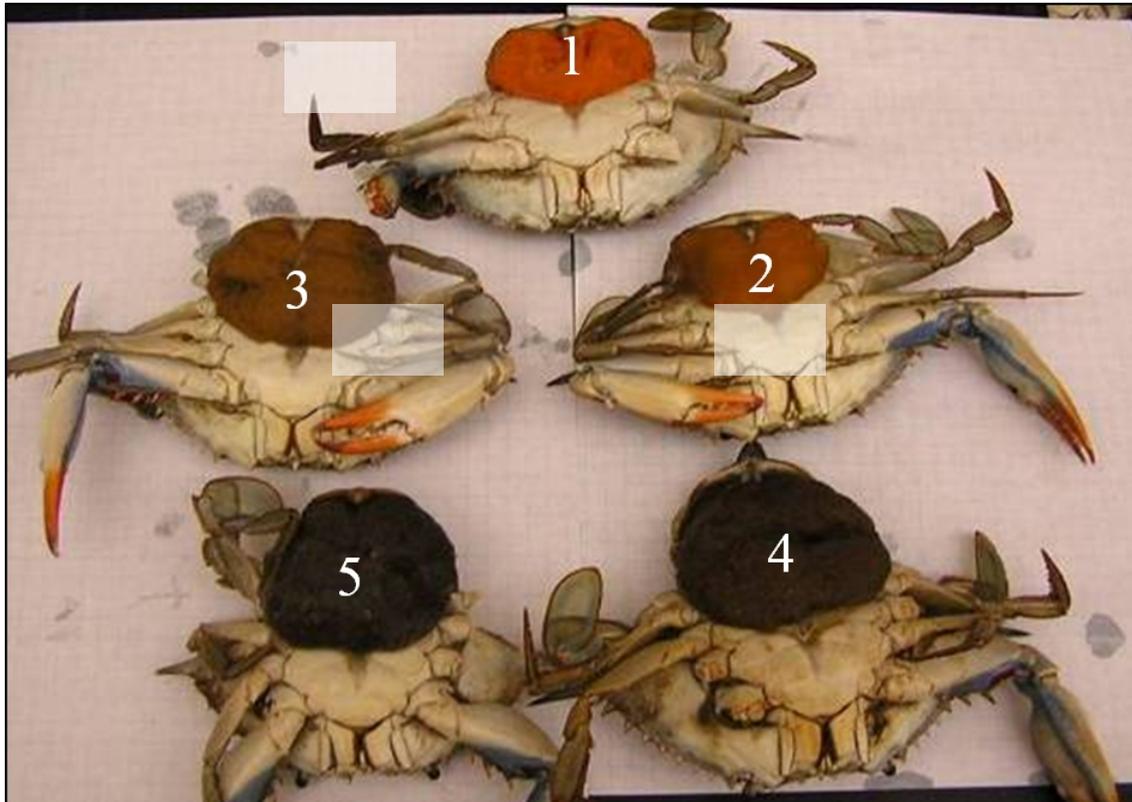


Figure 3. Ventral view of five female blue crabs of the Ship /Trinity/Tiger Shoal Complex with extruded sponges ranked according to developmental stage (1-5) of the sponge. The color change of the sponge is associated with the proliferation of pigments by the embryos as they develop. According to Jivoff et al. (2007) brood development takes approximately two weeks.

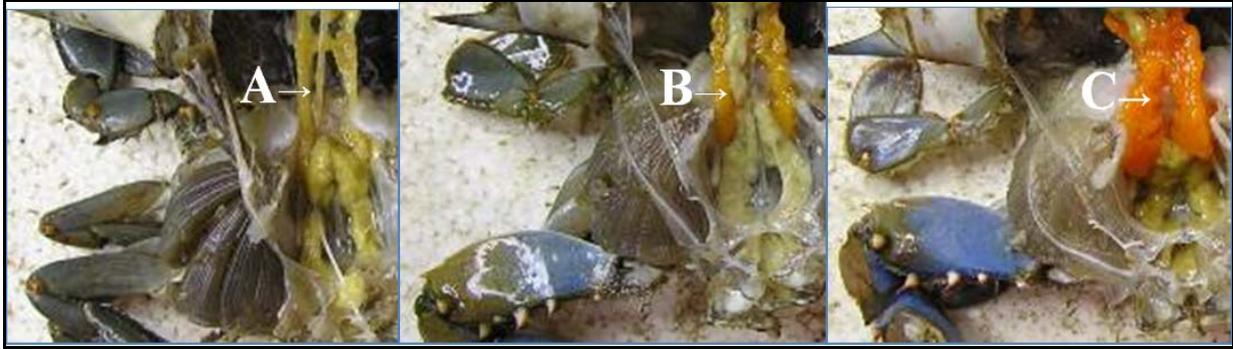


Figure 4. Interior view of mature female blue crabs of the Ship/Trinity/Tiger Shoal Complex displaying our three, Hard (1945)-based assessments of ovarian condition. (A) Light is consistent with both Hard's stage I where the ovary is described as "small, inconspicuous, white in color" and Hard's stage V where the ovary is described as "collapsed, grey or brownish in color." (B) Medium is consistent with Hard's stage II for ovaries of an intermediate size. (C) Full is consistent with Hard's stage III where the ovary is "preceding first ovulation...bright orange and of large size" or stage IV where the ovary is "between ovulations...orange in color and of large size."

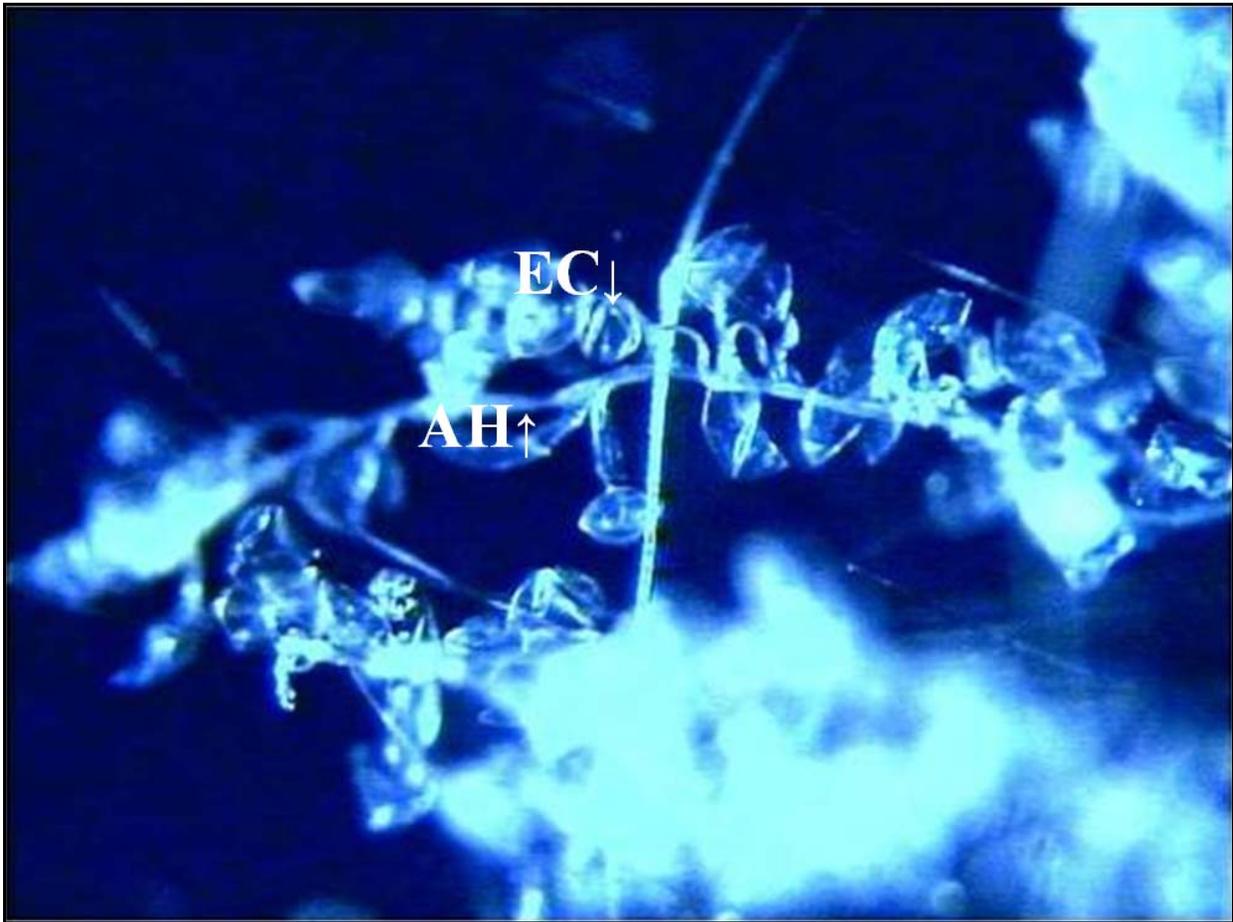


Figure 5. Microscopic image of hatched egg casings (EC) on individual abdominal hairs (AH) located on the pleopods of a female blue crab from the Ship/Trinity/Tiger Shoal Complex. These remnants are evidence that the female has spawned and hatched at least one previous sponge (Churchill 1919).



Figure 6. Examples of the most common symbionts of the Ship/Trinity/Tiger Shoal Complex blue crabs. Top left: Dorsal view of gills showing a high infestation of the nemertean *Carcinonemertes carcinophila* (light colored, encapsulated structures indicated by the probe). Top right: Ventral view of gills with high (> 200 individuals) infestation of the gooseneck barnacle *Octolasmis muelleri*. Bottom left: Dorsal view of a female blue crab with acorn barnacles attached to the carapace. Bottom right: Ventral view of a sponge infected with *C. carcinophila* which are particularly evident as thread-like structures inside the white box.

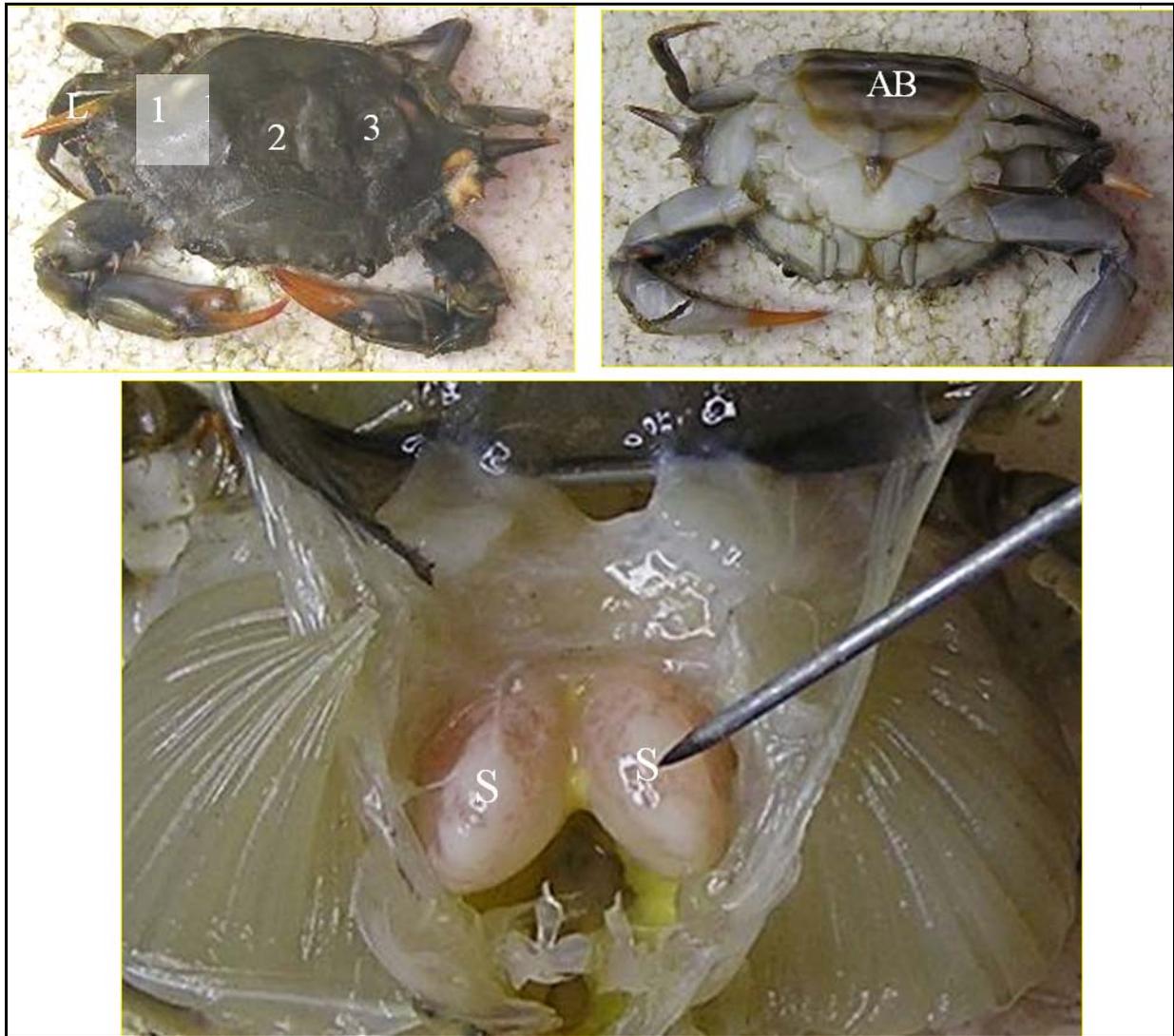


Figure 7. Three views of a female blue crab showing evidence of mating on the Ship/Trinity/Tiger Shoal Complex. Top left: Dorsal view showing signs of soft-shelled condition -- pliable dents in the carapace (1, 2, and 3) and downward bend of lateral spine (L). Top right: Ventral view showing rounded abdomen of mature female (AB). Bottom: Internal view showing two spermathecae engorged with ejaculate (S, tip of pointer). The condition of these spermathecae are entirely comparable to the description Jivoff et al. (2007, p. 261) provides of a female blue crab which has just copulated: “the easily visible pink seminal fluid, capped with a dense accumulation of white spermatophores”. Mechanical manipulation of these spermathecae revealed that they are also consistent with Wolcott et al.’s (2005), Scale 1, “hard plug” spermathecae for crabs which have mated within the past two weeks. The crab is also consistent with Hard’s (1945) stage I as the ovary is not readily visible, a condition Hard expects for female crabs which have recently mated during their terminal molt.

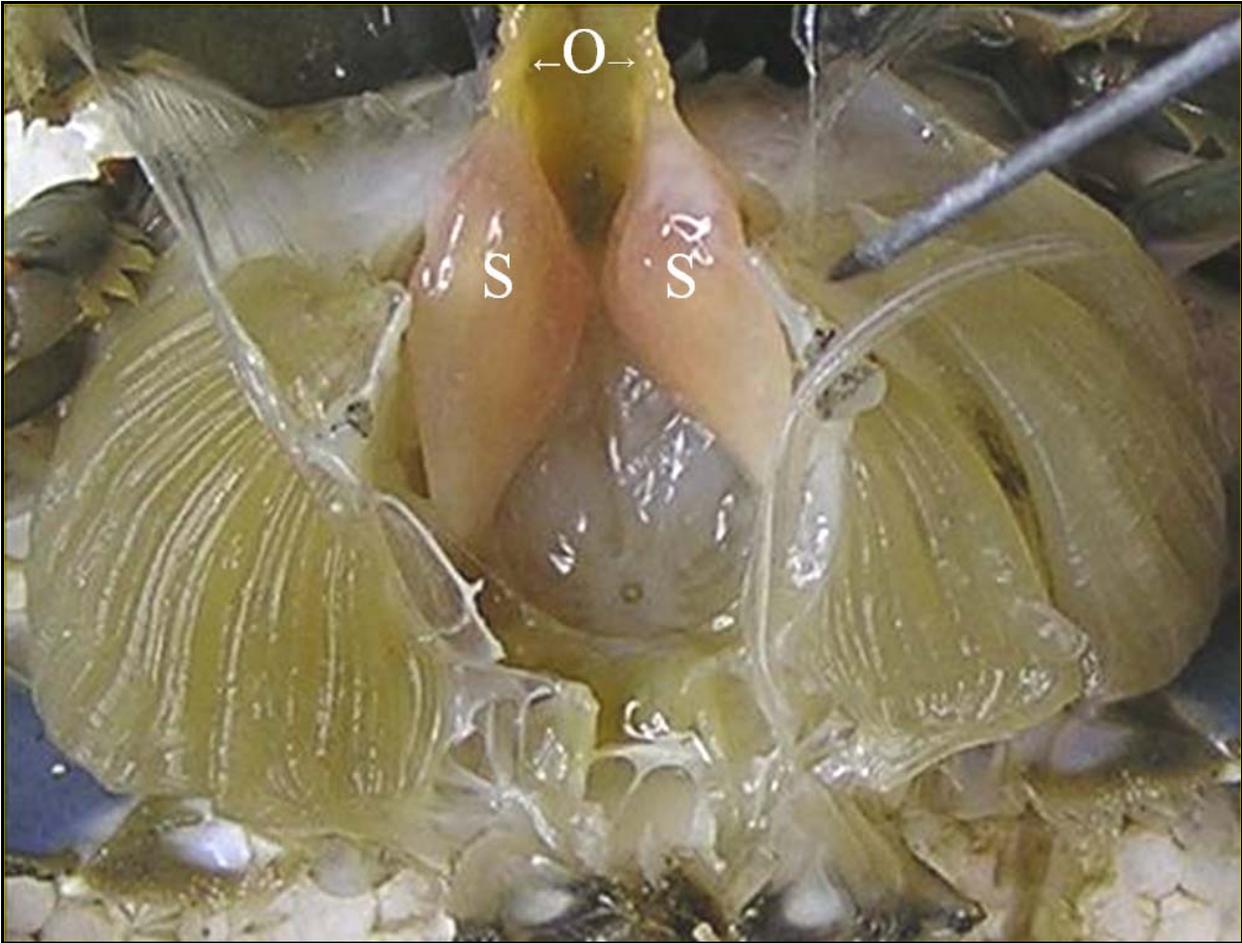


Figure 8. Interior view of a recently mated female blue crab from the Ship/Trinity/Tiger Shoal Complex with a hardened exoskeleton. The spermathecae (S) are beginning to soften and resorb. This crab is consistent with Wolcott et al.'s (2005), scale 2 in which a spermatheca appears as a “soft plug, in which the seminal fluid is softening.” The developing ovary (O) is consistent with Hard's (1945), stage 2, which describes the “growth period of the ovary, from the time of copulation to the time of ovulation” with a concurrent decrease in the size of the spermathecae.



Figure 9. Interior image of a mature female blue crab from the Ship/Trinity/Tiger Shoal Complex whose spermathecae (S) have decreased in size due to absorption of the seminal fluid. This particular female had evidence of a previous spawn in the form of hatched egg casings on her pleopods. As such she is consistent with of Wolcott et al.'s (2005) scale 5 which describes the spermathecae of a brooded female. Her full ovarian condition (O) indicates she is preparing to extrude another sponge and is consistent with Hard's (1945) stage 4, which describes the ovarian state between broods.

BLUE CRAB HYPOTHESES

As our project developed, we began to realize that the STTSC complex was an important spawning/hatching/foraging ground for female blue crabs and that we could develop useful statistical tools to detect adverse impacts of limited sand mining within the STTSC on its blue crab population(s). Our specific, testable hypotheses are:

1. There is no statistical difference in condition factor of the STTSC crabs and those from recognized blue crab spawning, hatching, and/or foraging grounds.
2. There is no statistical difference in size/fecundity relationship of blue crabs on STTSC crabs and those from recognized blue crab spawning grounds.
3. Mature female blue crabs on STTSC are in a continuous spawning/hatching cycle during at least April-October.
4. The conventional measure of blue crab size provides the best statistical tool to describe the dependence of blue crab weight on volume.
5. Condition factor and fecundity of blue crabs on the STTSC will not be affected by month, area, ovigery, parasitism by nemerteans in the gills or sponge, parasitism by goose neck barnacles in the gills, and fouling by acorn barnacles on the exoskeleton.
6. There are no temporal or spatial differences in the use of the STTSC as a blue crab spawning/hatching/foraging ground.
7. There is no statistical difference in mature female crab abundance between the STTSC and conventionally recognized blue crab spawning grounds.

MATERIALS AND METHODS

To test four hypotheses we used a combination of regression, stepwise multiple regression and ANCOVA analyses and took the following measurements of STTSC blue crabs obtained during spring, summer, and fall of 2006, and 2007:

- TT – carapace width between the lateral spines,
- BB – carapace width at the base of lateral spines,
- L – carapace length,
- H – carapace height,
- W – crab weight without acorn barnacles,
- T – tail weight
- C – body weight without tail (W – T),
- P – ovigerous/nonovigerous (presence/absence of a sponge),
- SC – sponge color on a five-point scale, bright orange (1) to black (5) (Figure 3),
- SN – nemertean intensity (*C. carcinophila*) on sponge (four-point scale, Figure 6),
- E – number of eggs (in millions) in a sponge
- BC – acorn barnacle (*C. patula*, *Balanus* spp.) exoskeleton coverage (10 point scale, Figure 6),
- BW – acorn barnacle weight,
- D – largest acorn barnacle diameter,
- O – ovary fullness on a three-point scale (Figure 4),
- G – gooseneck barnacle (*O. muelleri*) intensity on gills (six-point scale, Figure 6),
- GN – presence/absence of the nemertean *C. carcinophila* on gills; gill nemerteans (Figure 6).

The available literature allowed us to test hypotheses 1 and 2 with other areas, but required that we make a decision between using either wet weights and dry weights of our whole crabs. We chose to use wet weights of whole crabs as this allowed us to make the most comparisons.

All statistical analyses were done using version 9.1.3 of SAS (SAS Institute Inc. 2004). With the exception of the ANOVA used to test hypothesis 6, all of our results are significant at $p > 0.01$. For our test of hypothesis 6, we accepted differences at $p = 0.1$, as we did not wish our limited trawling effort to inadvertently discount the importance of an area/month within the STTSC as an important spawning/hatching/foraging ground. We used the “stepwise” procedure in our multiple regression analysis, allowing the default settings to regulate model selection.

To test hypothesis 6, we used ANOVA to compare temporal and spatial trends in our STTSC data obtained in spring, summer, and fall of 2007. To test hypothesis 7, we used the regression analysis to compare the peak catch rates we obtained in the STTSC in 2005, 2006, and 2007 with those reported in the literature for recognized blue crab spawning grounds.

The specific literature used to test hypotheses 1, 2, and 7 are briefly reviewed at the beginning of each of these sections in the section entitled **Test of Hypotheses**. The tests of hypotheses 1 and 4 required us to use the conventional measure of crab width found in the literature (TT). In testing hypothesis 4, we found TT to be statistically less predictive of weight than the other size measurements we took. We therefore included a brief review of relevant theory at the beginning of the section entitled **Test of Hypothesis 1**.

All linear measurements were made in mm; all weights, in g wet weight. All statistical analyses were conducted using SAS (Statistical Analysis System, Cary, NC). We did not transform our catch statistics as we used distribution free techniques available in SAS to analyze our STTSC catch data and because the aggregate data available in the literature was untransformed. Measurements made on Ship Shoal crabs in 2005 are consistent with those obtained for the STTSC in 2006 and 2007, but did not encompass the entire range of parameters we eventually measured, and are therefore not included in our condition factor analyses. A description of our sampling protocol is contained in Stone et al. (2009).

TEST OF HYPOTHESES

TEST OF HYPOTHESIS 1 (CONDITION FACTOR, NATIONAL COMPARISON)

The condition factor is the ratio of a fish's weight (W) to a linear estimate (X) of its volume (V). Usually length (L) is used as the measure of X. Condition factors are commonly used to compare the health of fish between differing populations, under the assumption that the heavier fish (per unit of length) are healthier (e.g., Ricker 1975). When W and X are measured over a range of sizes in at least two different populations, differences in the condition factor are normally tested using a form of the general size/weight relationship:

$$W = aX^b, \quad (1)$$

where a and b are constants (e.g., Newcombe et al. 1949). If the specific gravity is 1, $X=V$, and W and X are in g and cm^3 , respectively, then the constants 'a' and 'b' both equal one. When L is used to estimate volume, Equation 1 is called a length-weight relationship and has the form:

$$W = aL^b. \quad (2)$$

Equation 1 and Equation 2 can be fit directly to a data set using nonlinear statistics. Or the equations can be linearized:

$$\log W = \log a + b(\log X) \quad (1a)$$

$$\log W = \log a + b(\log L) \quad (2a)$$

and fit to the log transformed data using parametric statistical techniques. Since both procedures have their advantages and disadvantages (e.g., Ricker 1975), researchers normally examine the behavior of their data in both the transformed and untransformed state.

Statistical comparisons of condition factors between differing populations can be conducted using ANCOVA if the raw data are available or there are sufficient replicate equations per treatment. When an ANCOVA cannot be run because the raw data are unavailable or because there are insufficient replicate equations, regression analysis can be used to compare equations between differing populations. In the latter case, a regression of $\log a$ versus b should generate a single straight line with a negative slope and a random scatter of the residuals, unless the condition factor varies among the populations being considered. Though common in the literature, comparisons of slopes (b) without a consideration of the corresponding intercepts (a) is not an appropriate comparison of condition factors, since b is not independent of a. For example, a seasonal decline in specific gravity (as would occur with an increase in energy reserves stored as lipids) would theoretically depress b and increase a if the relationship between L and V remains constant.

With blue crab, it has become common to use the width of the carapace instead of length and to measure width (in mm) as the distance between the lateral spines on the carapace (TT) (Table 1).

The desirability of this convention has been questioned since the lateral spines are often damaged and different spine morphologies within the same population have been shown to have different predictive capacities (Olm and Bishop 1983). Regardless, the conventional measurement (TT) has not been tested against other linear measures of size.

Table 1

Published female blue crab width-weight equations, $W = aTT^b$, where W is either in wet weight (g) or dry weight (g) and TT is carapace width between the lateral spines (in mm).

Weight	Area	a	b	Source
Wet	Chesapeake Bay, VA/MD	0.000343	2.575	Newcombe et al. 1949
		0.003487	2.1165	Rothschild and Ault 1992
		0.000631	2.47	Lipcius and Stockhausen 2002
	Ashley River, SC	0.004185	2.1083	Olm and Bishop 1983
	Mississippi	0.0001810	2.7814	Perry in Guillory et al. 2001
	Galveston Bay, TX	0.0002874	2.6395	Pullen and Trent 1970
Dry	Delaware	8.9125	0.005	Hines 1982

To compare the condition factor of our STTSC crabs with those in Table 1, which used wet weight, we first fit our STTSC nonovigerous crab data to Equation 1a using TT as an estimate of X, and obtained:

$$\log W = -3.0739 + 2.3964 * \log TT \quad (3)$$

(residual sum of squares $[R^2] = 0.80$). Then we compared the published wet weight equations in Table 1 with Equation 3 by plotting the respective $\log(a)$ values against the respective values of b. We found a striking inverse relationship between $\log a$ and b:

$$\log(a) = 1.9065 - 2.0602 * b \quad (4)$$

($R^2 = 0.99$), Figure 10. These results suggest that all the individual length-weight equations considered conform to a single relationship for nonovigerous female blue crabs. As such our analysis finds no statistical difference in the condition factors for these populations of nonovigerous female blue crabs which range from Chesapeake Bay in the 1940s to the STTSC in 2006-2007. Based on this overall similarity in condition factors from all known blue crab studies, we are unable to reject hypothesis 1 and conclude that the STTSC currently supports a healthy habitat for spawning/hatching/foraging female blue crabs.

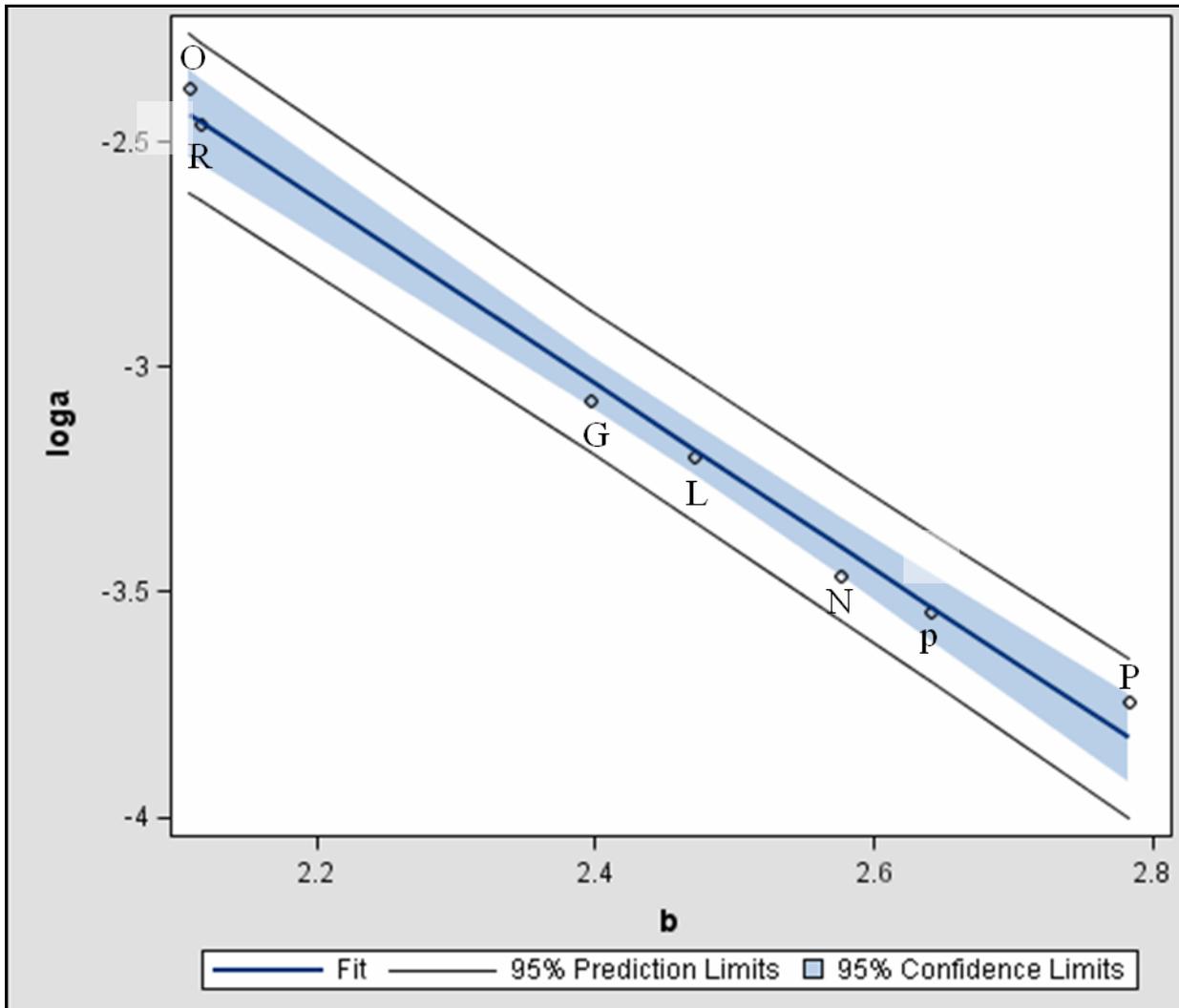


Figure 10. Results of a regression analysis run to test the hypothesis that the available width-weight equations ($\log W = \log a + b(\log TT)$, where W is g wet weight and TT is carapace width in mm between the lateral spines) for nonovigerous female blue crabs conform to a single family of curves. Open circles are the intercepts ($\log a$) and slopes (b) of width-weight relationships for Chesapeake Bay, VA/MD (N, Newcombe et al. 1949; R, Rothschild et al. 1992; and L, Lipcius and Stockhausen 2002), Ashely River, NC (O, Olmi and Bishop 1983), Mississippi (P, modified from Perry in Guillory et al. 2001), Ship/Trinity/Tiger Shoal Complex, LA (G, this report); and Galveston Bay, TX (p, Pullen and Trent 1970). The regression fit is $\log a = 1.9065 - 2.0602 * b$ ($R^2 = 0.99$).

TEST OF HYPOTHESIS 2 (FECUNDITY, NATIONAL COMPARISON)

We used an ANCOVA to compare the fecundity of our SSTTC crabs with that reported for Chesapeake Bay by Prager et al. (1990) with their dry weight procedure. We found no effect of area (Chesapeake Bay, STTSC) in the ANCOVA we ran of E on TT with area as a class variable. The single regression fit to the data,

$$\log E = -4.8453 + 2.1151 * \log TT, \quad (5)$$

($R^2 = 0.31$), Figure 11, predicts a linear increase in fecundity (measured in number of eggs/sponge) with increasing size of the mature female. The analysis finds no difference in the fecundity/size relationship of ovigerous crabs between the STTSC and Chesapeake Bay. We are unable to reject hypothesis 2 and conclude that the STTSC supports as fecund a population of spawning blue crabs as Chesapeake Bay did before its apparent decline in crab abundance.

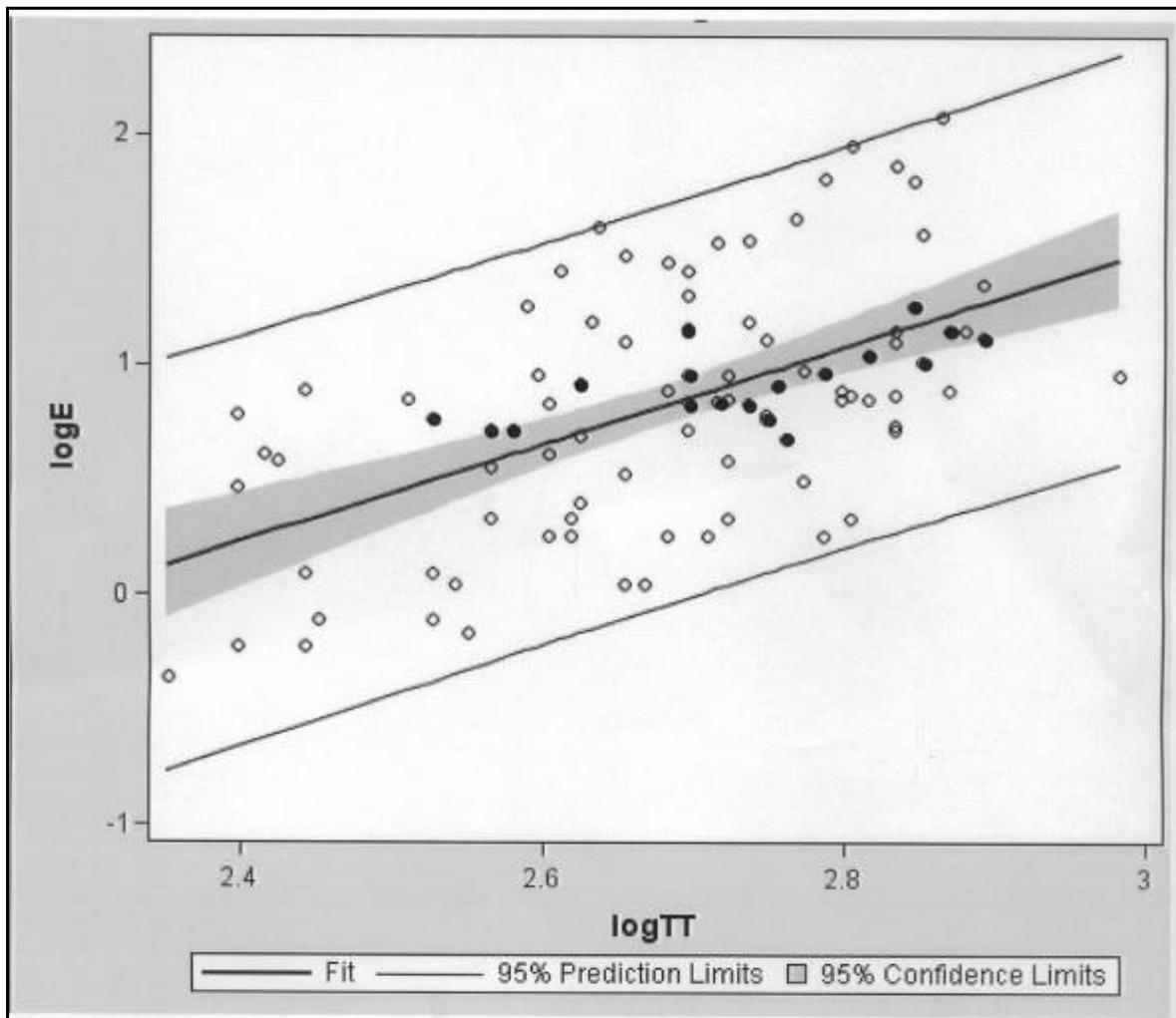


Figure 11. Results of an ANCOVA run to test the hypothesis that there is no difference in the fecundity-size relationships for mature female blue crabs from the Chesapeake Bay, VA/MD (open circles, Prager et al. 1990) and the Ship/Trinity/Tiger Shoal Complex, LA (closed circles, this report). The regression fit is $\log E = -4.8453 + 2.1151 \cdot \log TT$ ($R^2 = 0.31$), where E is millions of eggs/female and TT is width (cm) between the tips of the lateral spines of the carapace.

TEST OF HYPOTHESIS 3 (CONTINUOUS SPAWNING/HATCHING CYCLE DURING STUDY)

During our dissections, we noticed a general relationship between ovarian condition (Figure 4), the presence or absence of a sponge, and the color of the eggs on a sponge (Figure 3) when present. Generally we came to expect that nonovigerous crabs would have comparatively full

ovaries and that the ovarian fullness of ovigerous crabs would increase as embryo development increased (and the sponge changed from bright orange to black). The general impression was that ovarian recovery began immediately after spawning and continued at a constant rate through brooding so that a new brood would be spawned shortly after the present brood had hatched.

Based on these observations, we hypothesized that our female blue crabs were in a continuous spawning/hatching cycle on STTSC during at least April through October, and that they would undergo another spawn as soon as the ovary had recovered from the present spawn. Under this hypothesis, the ovarian condition of our nonovigerous females could be predicted by the rate of ovarian development exhibited by our ovigerous females. The simplest test we could develop for this hypothesis is: There was a linear increase in ovarian fullness, O , of our STTSC females from $O = 1$ (light ovary) after an existing brood had been spawned (time $T = O$) to $O = 3$ (full ovary) just before the next brood was spawned. In this simplest test, the average ovarian fullness of our nonovigerous females should occur at the predicted midpoint of the inter-sponge period.

To test this possibility, we first computed the average ovarian fullness by sponge color (O_{SC}); assumed (based on Jivoff et al. 2007) that each of our five sponge colors represented three days of embryo development time; and regressed O_{SC} against the respective estimate of average embryo age in days (t , where $t = 0$ at spawning). The result:

$$O_{SC} = 0.9908 + 0.0971 * t \quad (6)$$

($R^2 = 0.97$) describes a linear recovery in ovarian fullness between spawning and hatching of an existing brood and predicts that full ovarian recovery ($O = 3$) will occur 6d after hatching ($T = 21$) and that the average O_{SC} of our nonovigerous crabs will be attained at $t = 18$ d. Then we reran the regression, but included our measure of average ovarian fullness as occurring at 18d. The results (Figure 12) strongly suggest that the STTSC crabs were in a continuous spawning cycle, producing successive spawns every 21 d. As a result we cannot reject hypothesis 3.

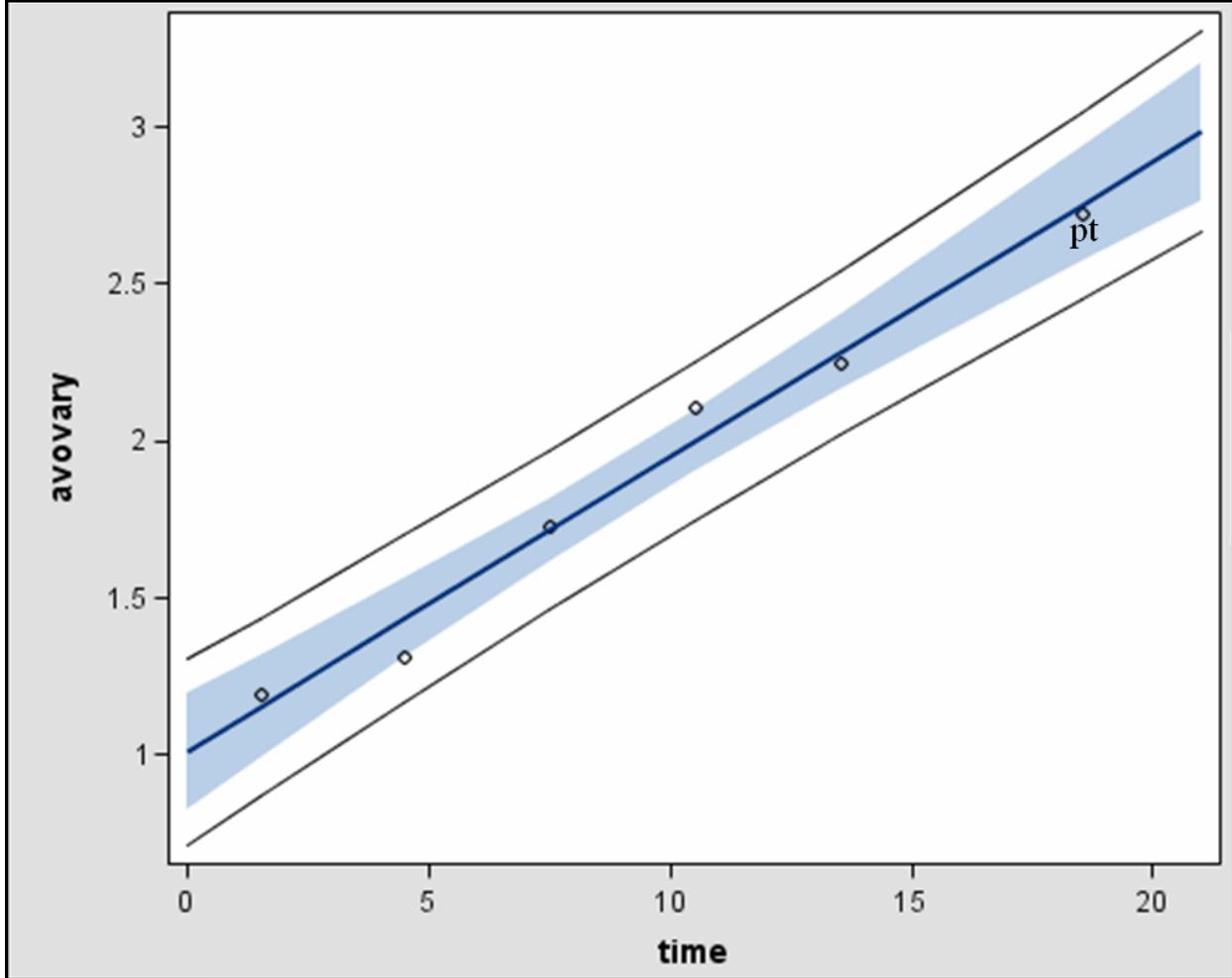


Figure 12. Testing the hypothesis that female blue crabs on the Ship/Trinity/Tiger Shoal Complex in April through October are in a continuous spawning/hatching cycle. In the test, the average ovarian development for crabs of differing sponge colors (O_{SC} , avovary, open circles) is first regressed against an estimate of embryo development time (t , time) derived using sponge color and Jivoff et al. (2007). The regression (not shown), $O_{SC} = 0.9908 + 0.0971 * t$, ($R^2 = 0.97$) is then used to predict the inter-brood period ($t-21d$). The "regression" shown is fit both to our data and to the prediction (pt) that the observed average ovarian condition of our nonovigerous crabs occurred at the midpoint ($t=18 d$) of the predicted inter-brood period.

TEST OF HYPOTHESIS 4 (TRADITIONAL ESTIMATE OF SIZE)

We ran a stepwise multiple regression analysis to find the most predictive linear measurement of body weight for female STTSC crabs by area and month. Here we tested the effect on W of TT ,

BB, L, H, P, month (M), and area (A for our five STTSC areas, Figure 1). The procedure selected a six parameter model of the form:

$$\log W = -3.2247 + 0.8071 * \log BB + 0.0843 * P + 1.5973 * \log L + 0.5918 * \log H - 0.0025 * M + 0.0023 * A \quad (7)$$

($R^2 = 0.968$) which uses three linear measures of size and ovigery, month, and area to predict weight. The procedure also revealed that a two-parameter model of the form:

$$\log W = -3.1743 + 0.0854 * P + 3.0017 * \log L, \quad (8)$$

($R^2 = 0.960$) provides as realistically good a fit as the six parameter model based on a comparison of model complexity and the minimal difference in R^2 's (0.008).

Both Equations 7 and 8 clearly indicate that the historically used TT is a poorer linear indicator of V than is L, H, or BB and that we should reject hypothesis 4. However, given the ubiquitous and long use of TT, we decided to examine the issue further through a series of ANCOVAs with P as a class variable and seven differing linear estimators of V in Equation 1a (L, H, TT, BB, L*H*BB, L²*BB, and L²*H).

The results are presented in Table 2. Based on a comparison of R^2 's, the three volume estimators, L*H*BB, L²*BB, and L²*H, provided slightly better predictors of weight than all single linear measurements. With single linear estimators, L was the most predictive estimator of weight ($R^2 = 0.961$), though followed closely by BB and H. The traditionally used TT was the least predictive ($R^2 = 0.806$).

Table 2

Comparison of size (X, mm) – weight (W, g) relationships for mature female blue crabs (n=388) from the Ship/Tiger/Trinity Shoal Complex, Louisiana, 2006-2007. Measurements of length (L), height (H), and width across the lateral spines (TT) follow Newcombe et al. (1949). BB is the carapace’s width between the bases of the lateral spines. Solutions are provided for the results of ANCOVAs testing the effect of ovigerity on the relationship $\log W = \log a + b(\log X)$, where X is varied as in column one, below. For each estimate of X, the base equation given is for ovigerous females. The corresponding equation predicting the weight of the nonovigerous females is obtained by adding c to log(a), and d to b. When d = 0, the ANCOVA’s interaction term is not significant and the equation reflects parallel slopes. Note that TT has the lowest R², and is therefore least useful in predicting weight.

X estimator	R ²	log(a)	b	c	d
Length (L)	0.961	-2.8452	2.8651	-0.5165	0.2424
Height (H)	0.925	-1.977	2.7446	-0.4573	0.2445
Width at base (BB)	0.942	-3.7103	2.9111	-0.0887	0
Width at tips (TT)	0.806	-2.3349	2.1025	-0.7394	0.2942
L*H*BB	0.966	-2.9455	0.9682	-0.4627	0.0706
L ² *BB	0.965	-3.1503	0.9636	-0.4846	0.0711
L ² *H	0.964	-2.6440	0.9601	-0.5105	0.0839

The comparatively poorer behavior of TT as an indicator of crab weight is graphically demonstrated in Figure 13, where we examine the fits obtained in Table 2 for BB and TT. Note the clearer separation of ovigerous and nonovigerous females when BB is used instead of TT to measure width. Varied lateral spine morphologies (Figure 14, Olmi and Bishop 1983) likely account for the poor predictive ability of TT as measure of carapace width and of volume.

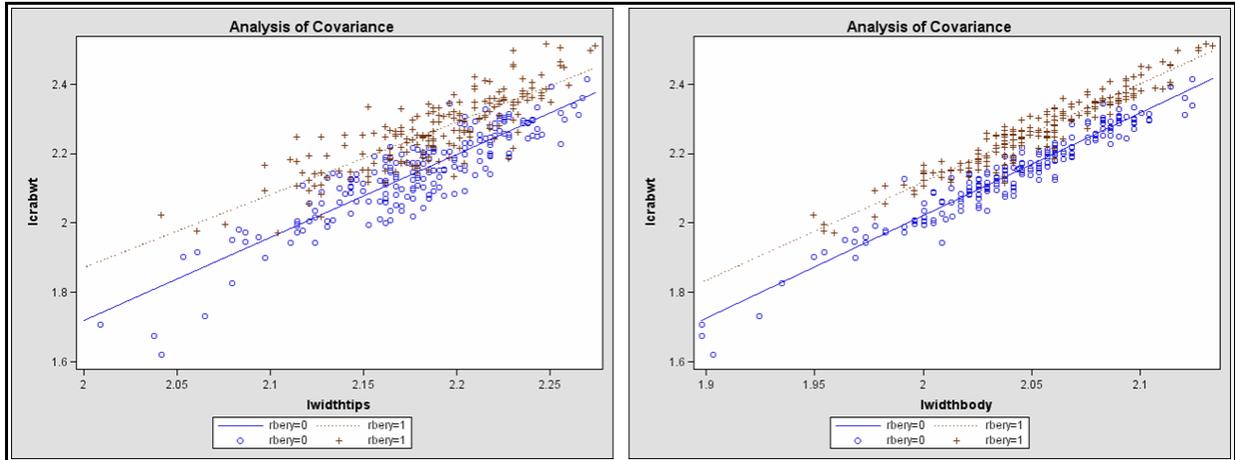


Figure 13. Graphical comparison of the ability of two measurements of carapace width to predict the weights (lcrabwt) of ovigerous (rbery = 1) and nonovigerous (rbery = 0) female blue crabs. Left: Width (lwidthtips) is measured as the distance between the tips of the lateral spines on the carapace. Right: Width (lwidthbody) is measured as the distance across the carapace between the bases of the lateral spines. Solutions to the regressions fitted to the data are included in Table 2. Note the much broader scatter of the data in the left graph, reflecting the much poorer ability of this measurement of size to predict weight.

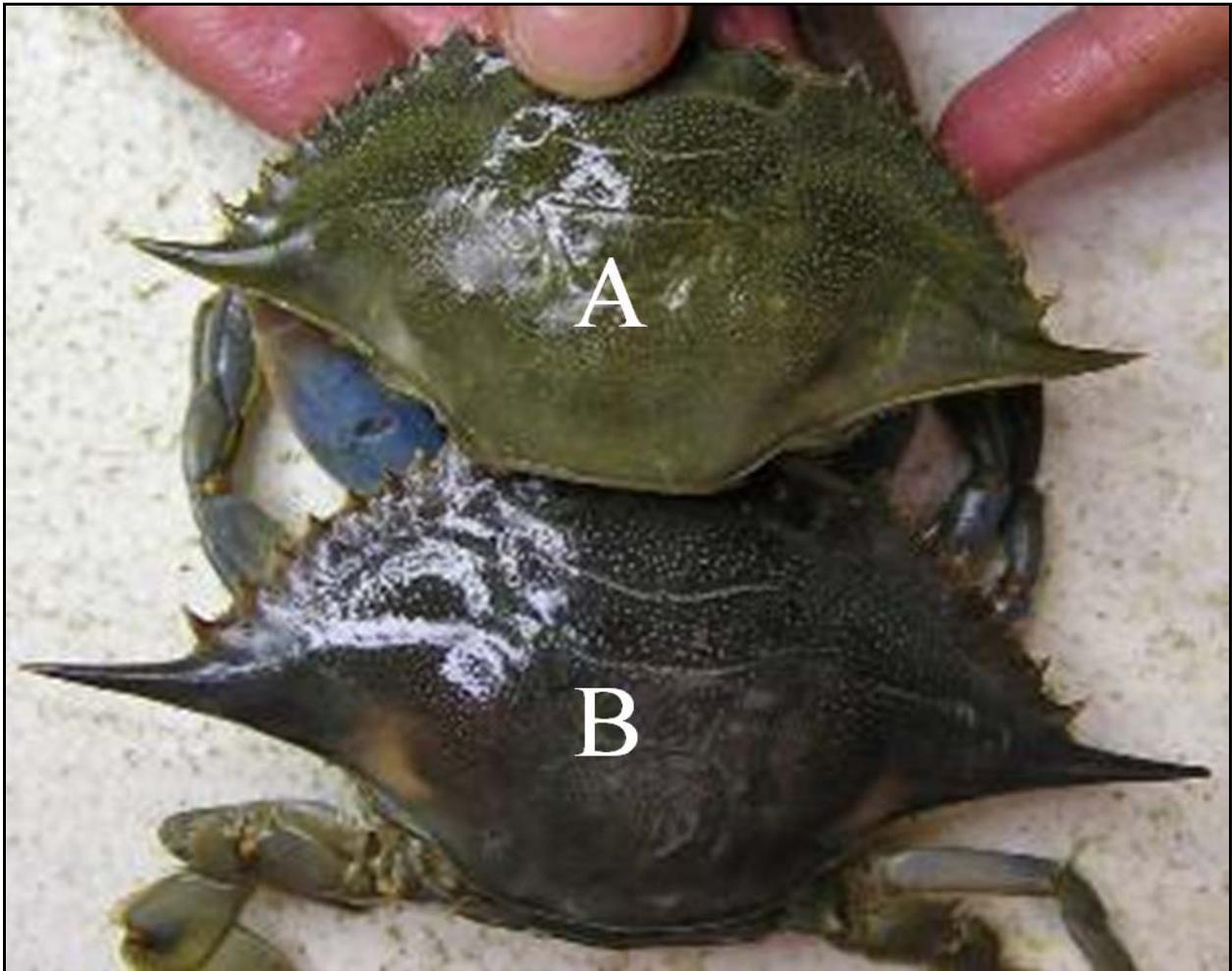


Figure 14. Dorsal view of the carapace of two similar size mature female blue crabs (A and B) from the Ship/Trinity/Tiger Shoal Complex displaying striking morphological differences of the lateral spines. The long-spined “acutidens” carapace form of Olmi and Bishop (1983) is represented by crab A, while their short-spined “typica” carapace form is represented by crab B.

Our results strongly suggest that TT should not be used as the primary measure of linear size in studies which wish to examine condition factors of blue crabs from differing environments/populations and that blue crab researchers begin replacing TT as the preferred index of blue crab size with some combination of L, BB, and H or a mathematical representation of V. As a result, we reject hypothesis 4.

TEST OF HYPOTHESIS 5 (FACTORS AFFECTING CONDITION FACTOR/FECUNDITY DURING STUDY)

As an overall test of hypothesis 5 we reran the stepwise regression procedure used to generate Equation 7, but also included SC, O, BC, BW, D, G, SN, and GN to examine the possible impacts on condition factor and fecundity of fouling, parasitism, ovarian condition, and embryo development stage. The stepwise procedure resulted in an eight parameter model in which TT was included as the final parameter with a partial increase in R^2 of 0.0003. Since we saw no compelling theoretical reason to suggest that V should be described by four linear estimates of size, we chose the seven parameter model for discussion:

$$\begin{aligned} \log W = & -3.1557 + 0.7472*\log BB + 0.0974*P + \\ & 1.6066*\log L + 0.5904*\log H + \\ & 0.0107*O + 0.0094*GN - 0.0016(M) \end{aligned} \quad (9)$$

($R^2 = 0.972$). With an $R^2 = 0.972$, Equation 9 provides slightly more explanation of the data than Equation 7, ($R^2 = 0.968$), though the complexity of Equation 9 makes it difficult to assign meaning to those parameters which have little predictability. As with Equation 7, L and P account for most of the variation in the data, $R^2 = 0.960$. Ovarian fullness, O, is entered as the fourth parameter generating Equation 9, and increases the R^2 by 0.0039. G precedes M in parameter selection, though the contribution of each is minimal (0.0012 and 0.0003 respective increases in R^2).

By excluding SC, BC, BW, D, G, and SN from the final model, the selection procedure suggests that these parameters were not as predictive of weight as those selected. There are a number of possible reasons for these exclusions. On one hand, SC is associated with P and O. Therefore, the main impact of SC could be explained by the presence of P and O in Equation 9. And in a somewhat similar fashion, A (a minor factor in Equation 7) is not included in Equation 9, suggesting that its effect is explained by one or more of the physiological variables which were included. On the other, BC, BW, D, and G are not included in Equation 9, suggesting that the level of acorn barnacle fouling and gooseneck barnacle infestation we observed did not affect the condition factor of our STTSC crabs.

By including O, GN, and M in Equation 9, the selection procedure suggests that these parameters have a predictive effect on weight. We used ANCOVAs to investigate each of these possibilities below.

Since ovarian fullness varied with ovigerity (Equation 6, Figure 12), we used the weight of the carapace (C) instead of the W in an ANCOVA run with O as a class variable in a regression of $\log L$ on $\log C$. The results:

$$\text{LogC} = a + 3.0511 * \text{logL},$$

where $a = -3.3054$ when $O = 1$,
 $= -3.3060$ when $O = 2$, and
 $= -3.2913$ when $O = 3$

(10)

($R^2 = 0.93$), suggests that an average "full" ovary increased the carapace weight by about 3.3% over a "light" ovary, Figure 15.

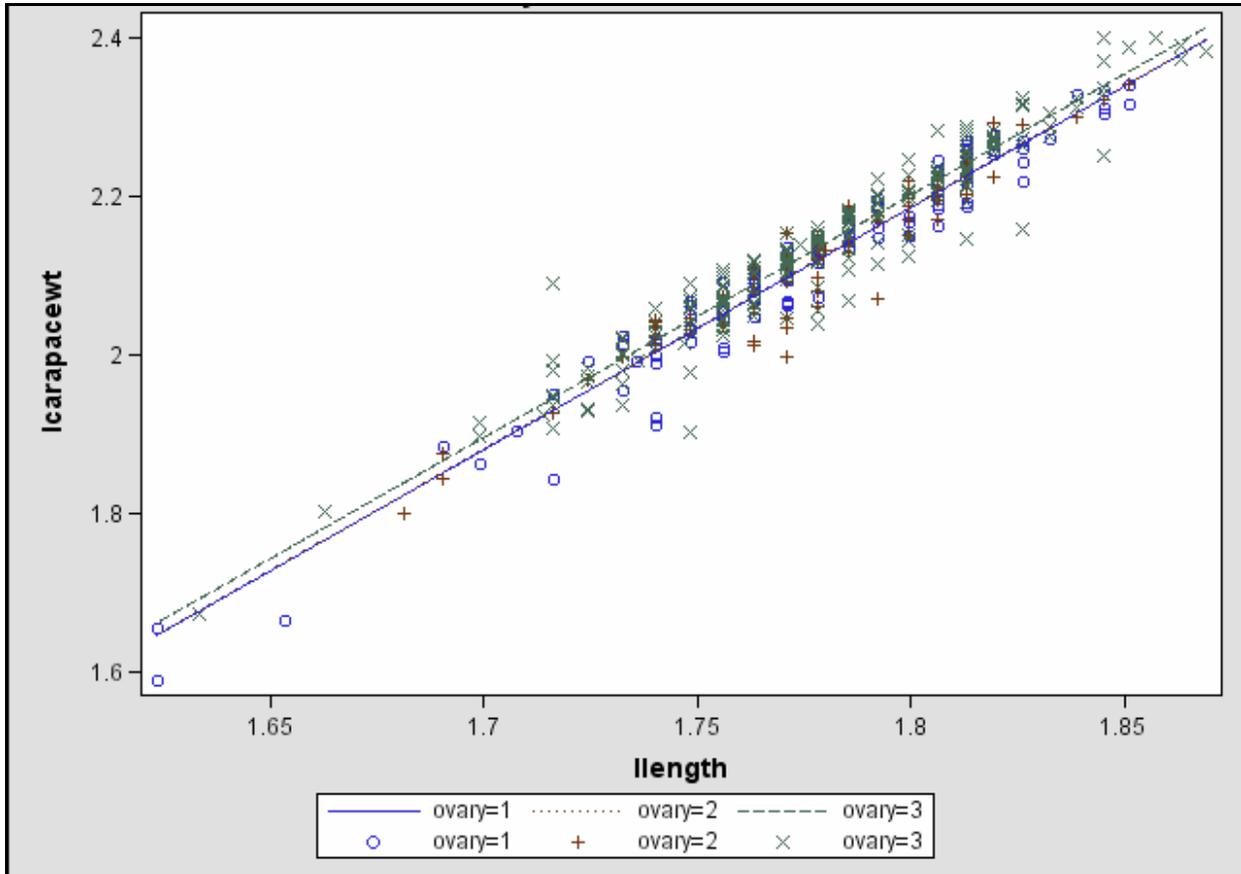


Figure 15. Results of an ANCOVA testing the effect of ovarian fullness (O, ovary) on the logarithmic relationship between carapace weight (logC, lcarapacwt) and length (logL, llength) for Ship/Trinity/Tiger Shoal Complex female blue crabs. The results predict that carapace weight will increase as O increases from 1 (light) to 3 (full). Lines fit to the data are the solution to: $\text{LogC} = a + 3.0511 * \text{logL}$, where $a = -3.3054$ when $O = 1$, $a = -3.3060$ when $O = 2$, and $a = -3.2913$ when $O = 3$ ($R^2 = 0.93$).

A similar ANCOVA run with GN as a class variable in a regression of logW on logL found a significant impact of nemerteans in the gills on the length-weight relationship of the form,

$$\log W = a + 3.2069 * \log L$$

where $a = -3.4903$ when $GN = 0$
 $= -3.5065$ when $GN = 1$

(11)

($R^2 = .86$). Equation 11 predicts that the presence of nemerteans in the gills will decrease the body weight by about 3.7%, Figure 16.

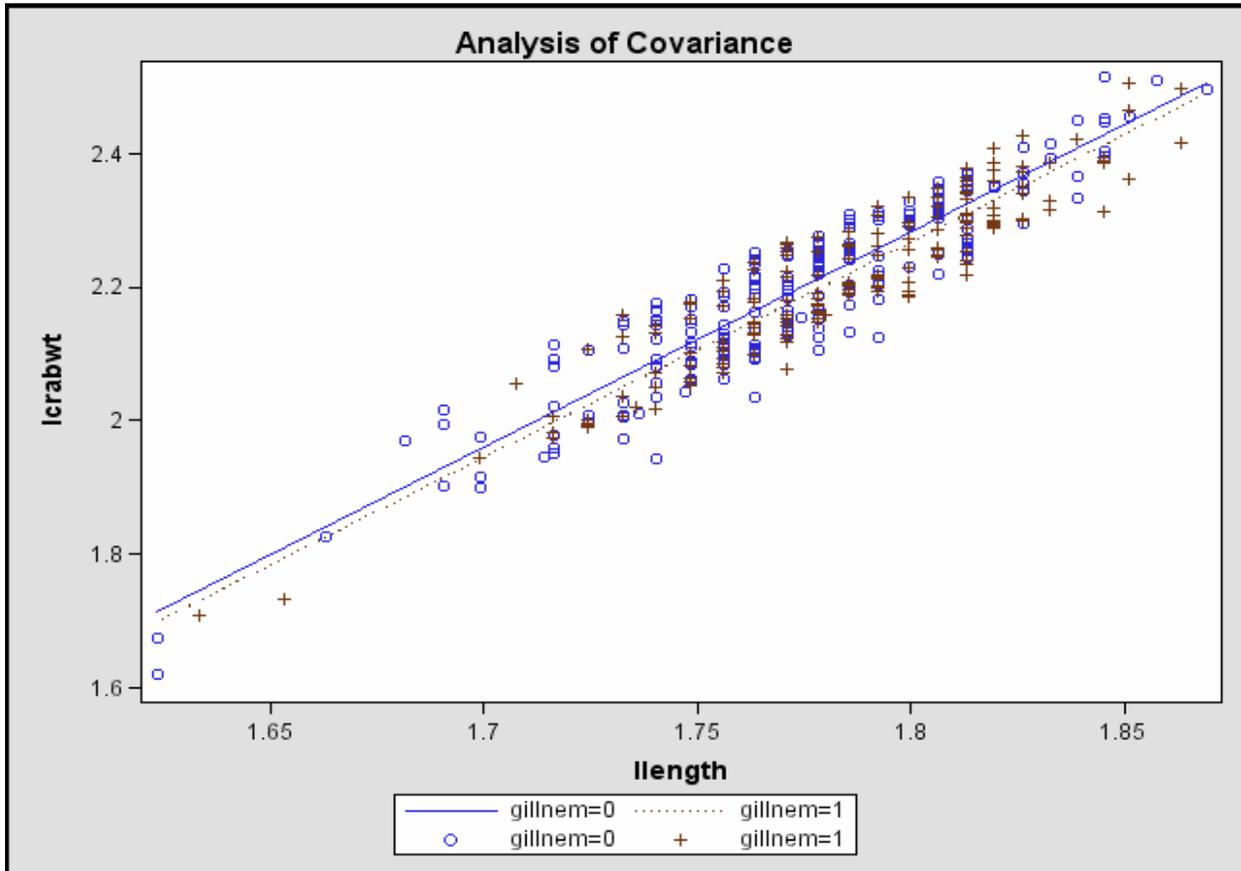


Figure 16. Results of an ANCOVA testing the effect of the presence/absence of the nemertean *Carcinonemertes carcinophila* (GN, gillnem) on the logarithmic relationship between crab weight ($\log W$, lcrabwt) and length ($\log L$, llength) for Ship/Trinity/Tiger Shoal Complex female blue crabs. The results predict that the presence of *C. carcinophila* in the gills will decrease body weight. Lines fit to the data are the solution to: $\log W = a + 3.2069 * \log L$ where $a = -3.4903$ when $GN = 0$ and $a = -3.5065$ when $GN = 1$ ($R^2 = .86$).

To examine our data for a possible minor effect of month on weight, we hypothesized that the monthly decline in prey abundance we are observing in the infauna samples we have collected (Dubois et al. 2009) would have a negative impact on the weight of the sponge due to ingestion-limited growth. To test this possibility, we regressed $\log T$ on $\log L$ with month as a class variable. Here our data limited us to a consideration of ovigerous crabs with well developed embryos ($SC > 3$, brown and black sponges). The ANCOVA revealed a significant main effect of month. The predicted regression,

$$\log T = a + 2.1014 * \log L,$$

where $a = -2.0596$ for April,
 $= -2.0949$ for May,
 $= -2.1284$ for August, and
 $= -2.1388$ for October

(12)

($R^2 = 0.60$), suggests that the observed weight of black/brown sponges for a given length interval of STTSC crab will decline at a fairly constant monthly rate (Figure 17). As a result of this decline, the sponge of a given length interval of crab will be approximately 20% lighter in October than expected in April. The result is consistent with the hypothesis that a seasonal decline in crab prey abundance limited crab egg production and suggests that the effect of month on crab weight may be due to ingestion-limited growth.

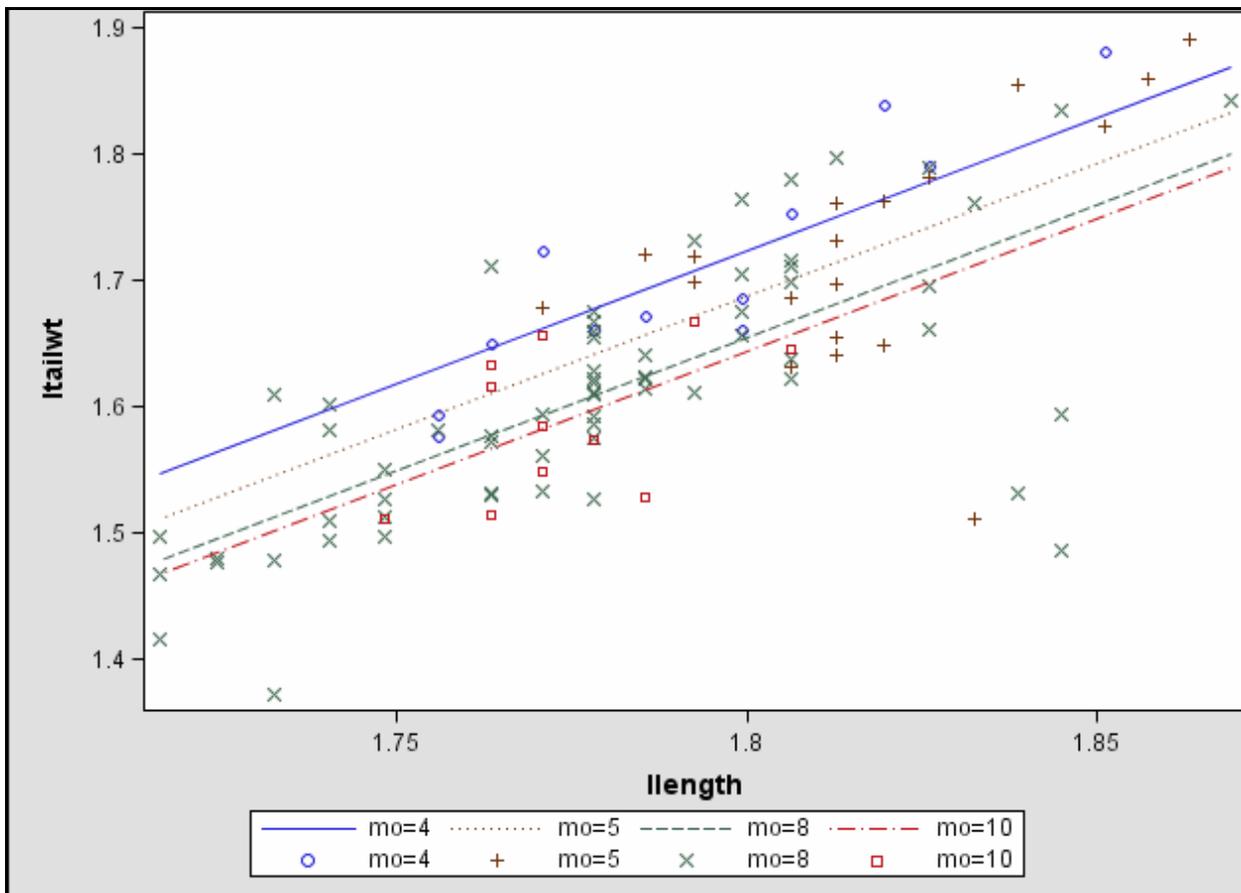


Figure 17. Results of an ANCOVA testing the effect of the month (M) on the logarithmic relationship between tail weight ($\log T$, ltailwt) of ovigerous crabs with well developed embryos and length ($\log L$, llength) for Ship/Trinity/Tiger Shoal Complex blue crabs. Lines fit to the data are the solution to: $\log T = a + 2.1014 * \log L$, where $a = -2.0596$ for April, $a = -2.0949$ for May, $a = -2.1284$ for August, and $a = -2.1388$ for October ($R^2 = 0.60$).

While the results of our ANCOVAs suggested that the effects of O, GN, and M we noted in Eq. 9 could be real, we remained interested in the effect of SC on weight for two reasons. First, we expected that dry weight of the embryos would decline with development stage due to metabolism of the yolk. Second (and conversely), we expected wet weight of the embryos would increase with hydration as the embryos approached hatching (e.g, Davis 1965). To test for an effect of development stage on the weight of our embryos, we ran an ANCOVA in which we regressed logT for ovigerous crabs on logL with sponge color, SC, as a class variable. We obtained:

$$\begin{aligned} \log T &= a + 2.2808 * \log L, \\ \text{where: } a &= -2.4842 \text{ when } SC = 1, \\ &= -2.4759 \text{ when } SC = 2, \\ &= -2.4510 \text{ when } SC = 3, \\ &= -2.4310 \text{ when } SC = 4, \text{ and} \\ &= -2.4391 \text{ when } SC = 5, \end{aligned} \tag{13}$$

($R^2=0.59$) which suggests a fairly sudden increase in the wet weight of the tail as SC increases above 2 (Figure 18). Equation 13 suggests an approximate 10% increase in wet weight of the eggs as they mature, probably reflecting hydration.

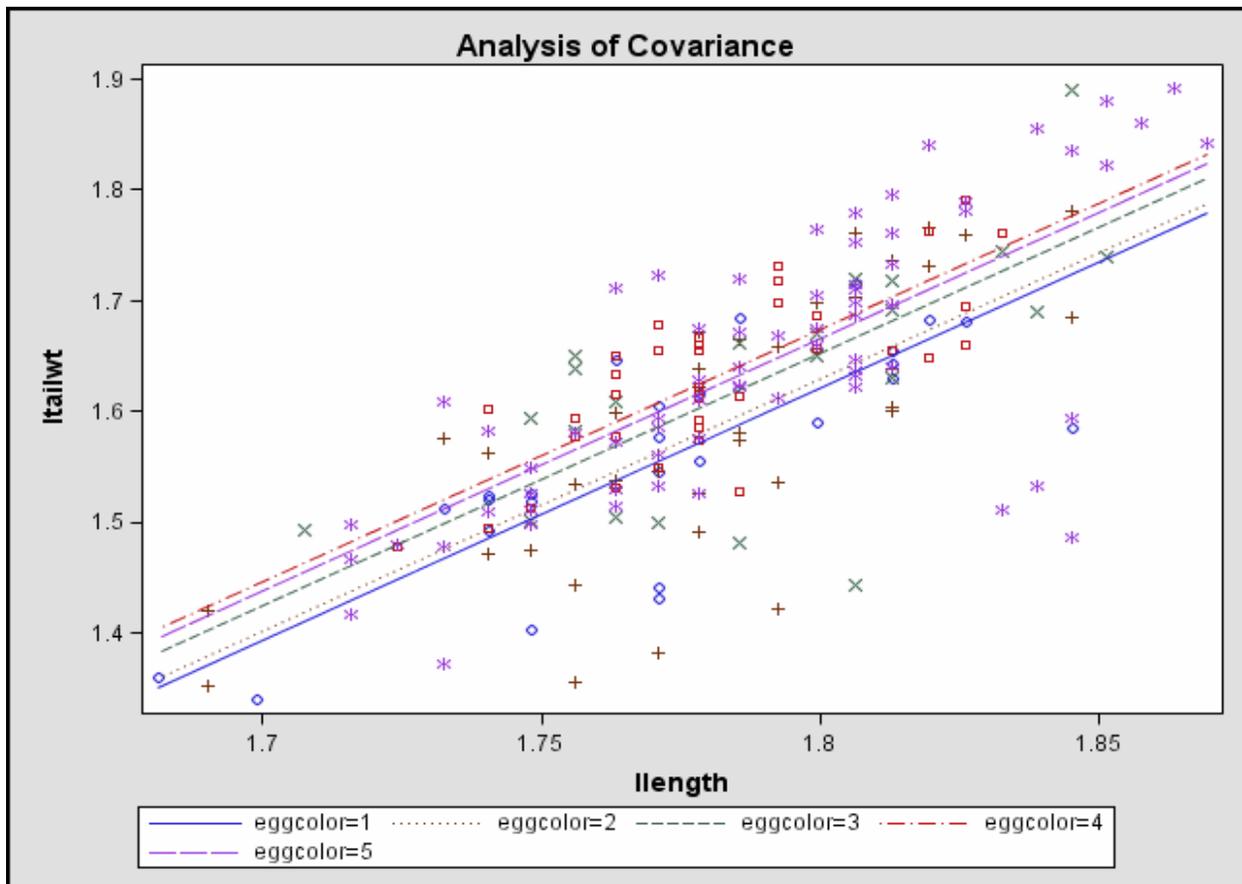


Figure 18. Results of an ANCOVA testing the effect of the embryo development stage represented by sponge color (SC, eggcolor) on the logarithmic relationship between tail weight (log T, ltailwt) of ovigerous crabs and length (logL, llength) for Ship/Trinity/Tiger Shoal Complex blue crabs. Lines fit to the data are the solution to: $\log T = a + 2.2808 * \log L$, where: $a = -2.4842$ when $SC = 1$, $a = -2.4759$ when $SC = 2$, $a = -2.4510$ when $SC = 3$, $a = -2.4310$ when $SC = 4$, and $a = -2.4391$ when $SC = 5$ ($R^2 = .59$).

Based on these analyses we reject hypothesis 5. We accept the likelihood that O, GN, and prey availability have a meaningful effect on crab weight in our study and conclude that our overall approach provides a meaningful technique to monitor the impact of sand mining on the condition factor and reproductive vigor of STTSC crabs.

TEST OF HYPOTHESIS 6 (TEMPORAL/SPATIAL ABUNDANCE PATTERNS DURING STUDY)

We ran an ANOVA on our 2007 STTSC data comparing mean catch rates as a function of month (April, August, and October) and area (Ship Shoal, Trinity Shoal, Tiger Shoal, Offshore area, and inshore area (Figure 1)). The results, Figure 19, suggests that mature female crab abundance

1) peaks on Ship and Trinity Shoals in August, 2) is substantial on Ship and Trinity Shoals from at least April through October and on the STTSC Inshore area in April through August, and 3) occurs throughout the remainder of the STTSC study area at a reduced level in April through October. Mean area catch rates across all months and mean monthly catch rates across all areas were significantly different from zero. Across all months, both Ship Shoal and Trinity Shoal had significantly greater mean monthly-area catch rates than the offshore area and Tiger Shoal. Mean monthly catch rates across all areas in August were significantly higher than April and October. Mean August catch rates for Ship and Trinity Shoals were significantly greater than those from the offshore area and Tiger Shoal for all months and from the Inshore area in October.

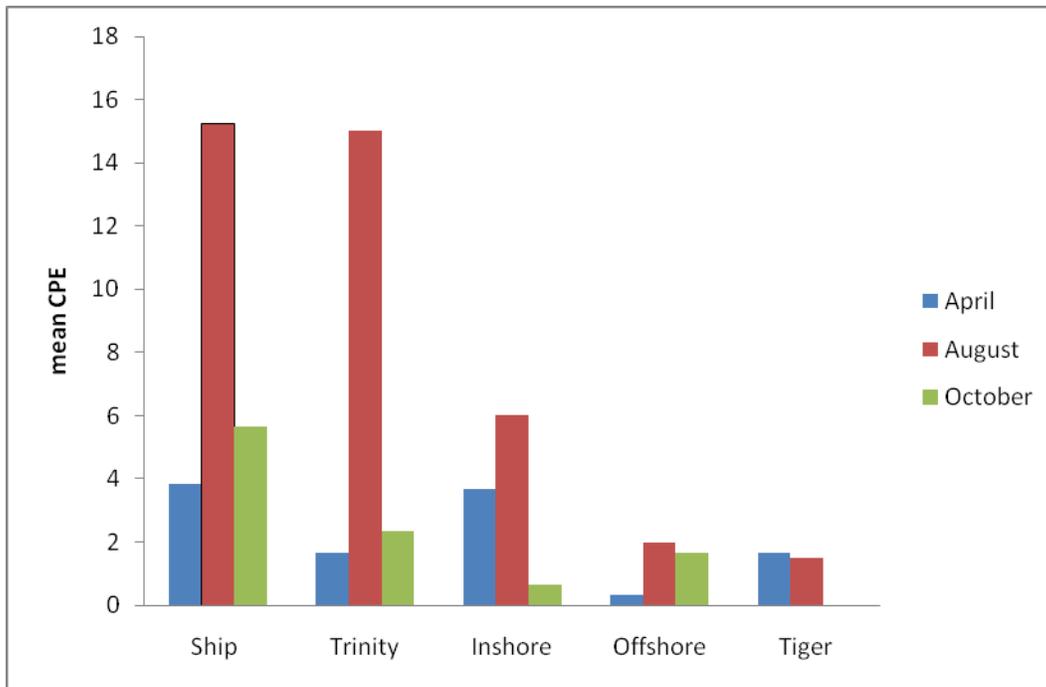


Figure 19. Comparison of mean catch rates of mature female blue crabs by area and month for the Ship/Trinity/Tiger/Shoal Complex in 2007. The August means for Ship and Trinity Shoals are significantly different ($\alpha=0.1$) from those of the Offshore area and Tiger Shoal for all months as well as for the Inshore area in October.

Given the results of our ANOVA (Figure 19), we reject hypothesis 6 and suggest that the abundance of spawning/hatching/foraging female blue crabs in the STTSC will peak on Ship and Trinity Shoals in August.

TEST OF HYPOTHESIS 7 (SPAWNING GROUNDS, NATIONAL COMPARISON)

Fishery independent catch rates of mature female blue crabs in areas recognized as blue crab spawning grounds are reported by More (1969) for Galveston Bay, TX; Adkins (1972) for Terrebonne Bay, LA; Archambault et al. (1990) for Charleston Harbor, SC; Lipcius and

Stockhausen (2002) for Chesapeake Bay, VI/MD; and Eggleston et al. (in review) for Pamlico Sound, NC. Size and duration of the trawl effort vary across these studies, as do number of areas sampled, duration and timing of study, and temporal aggregation of the published data. Most of the published studies represent at least two years of sampling and report their data in monthly averages by area. Lipcius divides his catches into two periods: one of high abundance, and one of low. None statistically compare their catch rates with other, geographically-different studies.

We calculated the average peak catch rates of mature female blue crabs by area/month/gear on a catch per month basis for each of the above studies and for our study, adjusting all average catch rates to 30 minutes of trawl time. We regressed the adjusted average peak catch rates (PC) against the width of the trawl (TW). The result:

$$PC = 44.5221 - 2.9142 * TW \quad (14)$$

($R^2 = .47$; Figure 20) suggests that peak catch rates of mature female blue crabs on these known or suspected spawning grounds are fairly consistent with a simple, single linear relationship which predicts that catch rates will decline with an increase in the size of the trawl used to sample the population. This decline, if real, may be more a function of vessel size than trawl efficiency, since most studies of blue crab spawning grounds have been conducted in 'shallow' waters. Given these results, we cannot reject hypothesis 7, and conclude that the available abundance data support the concept that STTSC is an important blue crab spawning ground.

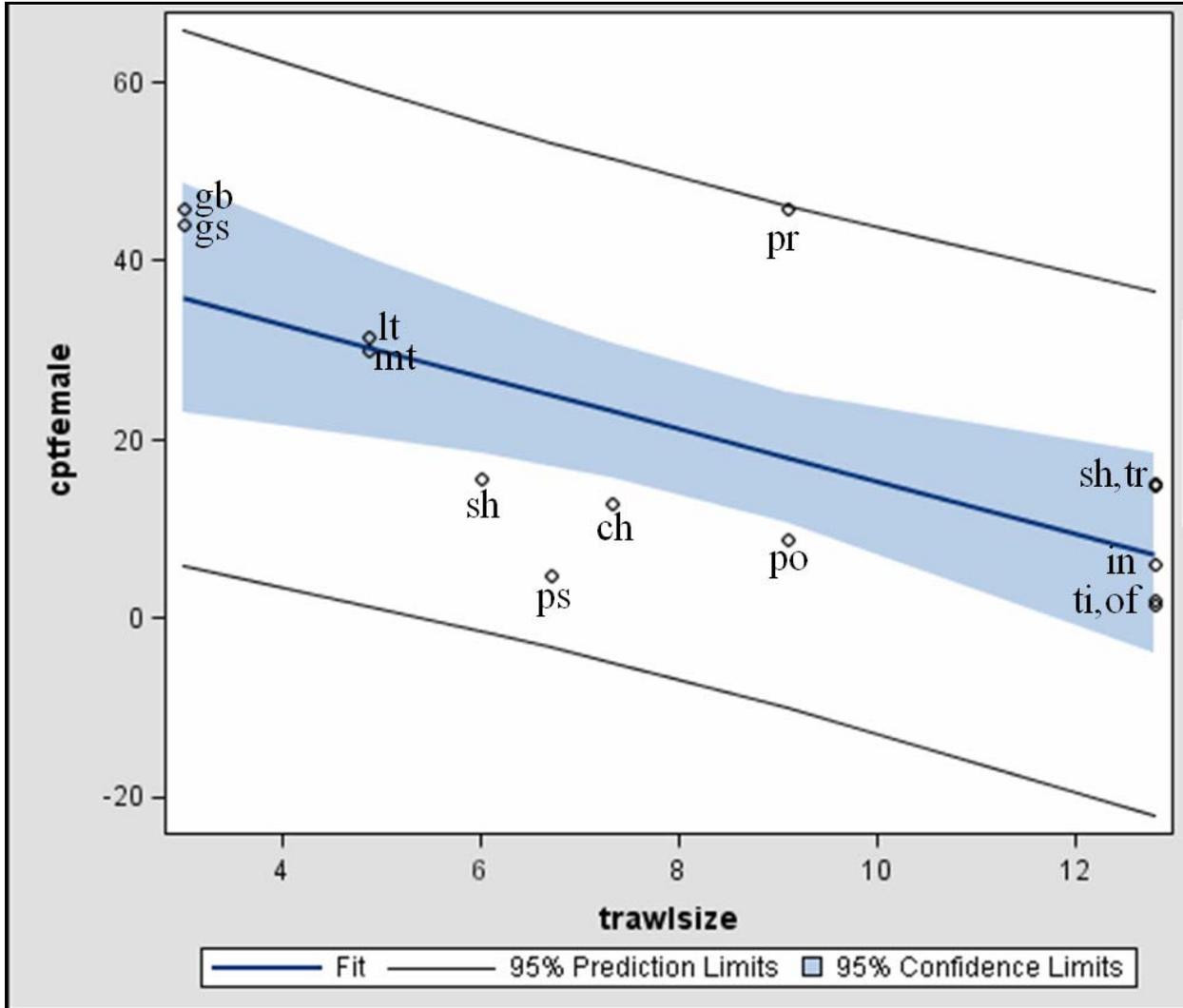


Figure 20. Results of a regression comparing average peak catch rates of mature female blue crabs by area/month/gear (PC, number/30 min) with width of trawl (TW, trawlsizem) from recognized blue crab spawning grounds and our study areas. Points plotted are from More (1969, Galveston Bay=gb and Gulf surf=gs), Adkins (1972, mt=middle Terrebonne Bay and lt=lower Terrebonne Bay, LA), Archambault et al. (1990, ch=Charleston Harbor, SC), Lipcius and Stockhausen (2002, pr=pre-phase shift and po=post-phase shift Chesapeake Bay, VI/MD), Eggleston et al. (in review; ps=Pamlico Sound, NC), and this study (sh=Ship Shoal, tr=Trinity Shoal, ti=Tiger Shoal, in=Inshore, and of=Offshore). The regression fit to the data is $PC = 44.5221 - 2.9142 \cdot TW$ ($R^2 = 0.47$).

RECOMMENDATIONS BASED ON THIS RESEARCH

SUMMARY OF FINDINGS

The STTSC is a nationally important, though unprotected, offshore blue-crab spawning/hatching/foraging ground from at least April through October, and an offshore blue crab mating site. During April-October, mature female crabs appear to be in a continuous spawning cycle, producing new broods approximately every 21 days while actively foraging to supply the necessary energy for this continuous reproductive activity. Egg production apparently declines slightly as the season progresses, perhaps reflecting some ingestion-limited growth of the ovary as infaunal prey densities decline. Condition factor appears to be positively associated with increases in ovarian condition and the presence of nemerteans (*C. carcinophila*) on the gills and negatively affected by a seasonal decline in prey abundance, but does not appear to be negatively impacted by acorn barnacles (*C. patula* and *Balanus* spp.) on the exoskeleton, gooseneck barnacles (*O. muelleri*) on the gills, or nemerteans (*C. carcinophila*) in the sponge (all conditions normally associated with higher salinity waters). Within the STTSC, Ship and Trinity Shoals appear to be the most important spawning/hatching/foraging grounds, especially in August.

During our sampling, we did not notice any apparent relationship between blue crab condition factor and any of the physical/chemical parameters we measured. In our 2005 and 2006 sampling on Ship Shoal, we did begin to see the possibility of a positive relationship between blue crab abundances and oxygen. We are currently exploring the relationship between blue crab abundance and oxygen concentration under separate MMS funding of our current STTSC project. However, when viewed in light of our national comparisons of blue crab condition factor, fecundity, and abundance, we believe that the overall environmental conditions we encountered on Ship Shoal in 2005 and 2006 and on the STTSC in 2007 are favorable for a continuous and highly successful blue crab spawning/hatching cycle during at least April through October, provided environmental conditions and fishing pressure do not change.

RECOMMENDATIONS

Statistical analyses conducted here suggest that STTSC blue crabs are healthy and fecund and that the indices and techniques developed and used in this report can be successfully used to monitor the impact of limited sand mining on these crabs. We recommend that at a minimum this monitoring program use box cores and either trawls or crab traps and be designed to test for changes in infaunal abundance and composition, as well as blue crab abundance, reproductive and body weight condition factors. Appropriate morphometric and condition-factor indices include: multiple measures of body volume, extent of parasitism and fouling,

presence/viability/development stage of sponge, stage of ovarian development, concentration/viability of stored sperm, and lipofuscin concentration (for ageing). Additional studies are needed, however, to suggest how limited sand mining operations on the STTSC may affect blue-crab larval survival and recruitment to Louisiana's estuaries and whether the presence of blue crabs makes the STTSC an important seaturtle foraging ground (i.e., Seney and Musick 2007).

A continuance of the cautious approach to sand mining being exhibited by MMS for the STTSC is recommended, given the possibility that fecundity of blue crab on the STTSC becomes seasonally limited by prey abundance under prevailing natural conditions. In addition, recent studies within coastal Louisiana (Palmer et al. 2008) showed significant sand mining related declines in macrofaunal abundance, biomass, and diversity.

A comparison of our results with the available literature suggests that the techniques employed here could enhance our understanding of other blue crab populations.

Finally, there does not appear to be a directed fishery currently operating on the female blue crabs in the STTSC and the current social norm in Louisiana, the Gulf, and Nation seems to favor a protection of spawning crabs. This lack of a directed fishery on the reproductively active STTSC crabs likely enhances the stability of Louisiana's traditional inshore blue crab fishery. A conservative management strategy would assure the stability of the current inshore blue crab fishery by protecting STTSC blue crabs from a directed harvest until their contribution to the health of the current inshore fishery can be assessed. National efforts to restore the Chesapeake Bay and North Carolina populations have found no inexpensive "quick fixes". For example, Chesapeake Bay stock enhancement scientists "expect the production cost of blue crab juveniles will be . . . in the range of U.S.\$0.15-30/juvenile" and that there will be a "10% survival of cultured females until spawning in the sanctuary" (Zohar et al. 2008). Under this scenario, the hatchery costs associated with the arrival of mature ("hatchery") female blue crabs on the spawning grounds would be \$18 to \$36/dozen, or approximately the current retail price of blue crabs in the Louisiana market.

At the conclusion of this contract, it is not clear whether the lack of an abundance of white and brown shrimp on Ship Shoal is a function of the natural life history of these species, surrounding hypoxic conditions, or reductions in offshore abundances associated with current, habitat-wide levels of young-of-the-year harvest. However, since we did not find an abundance of white and brown shrimp on Ship Shoal, it is not surprising that we did not find indicators of an abundance of spotted seatrout, given our understanding of predator-prey relationships. Regardless, it is clear that the STTSC is an important spawning, hatching, and foraging ground for mature female blue crabs. And, we believe, that the multiple regression/ANCOVA BACI approach we have developed can be successfully used to monitor the impact of limited sand mining on the condition factor and reproductive vigor of mature female blue crabs.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.



The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.