Abstract

CHAVES, JUAN CARLOS**.** Biological and Operational Factors Causing Mortality in North Carolina's Soft Shell Blue Crab Industry (Under the direction of David B. Eggleston.)

Factors causing mortality in North Carolina's soft-shell blue crab industry were quantified and identified at 11 crab shedding systems across the state. Operators of crab shedding systems who shed peeler crabs (pre-molt crabs) that they had caught themselves (self-caught peeler crabs) experienced significantly lower crab mortality rates than operators who shed peelers that they had bought from different sources (purchased-peeler crabs). Molt stage had a significant effect on the mortality rates of self-caught peeler crabs, as early molt stage crabs (white-line peelers) suffered significantly higher mortality rates than late molt stage crabs (red-line peelers). Purchased male crabs experienced significantly higher mortality rates than purchased females crabs. Water quality did not have a significant effect on crab mortality. Male peeler crab mortality was not significantly affected by the presence or absence of female red-line peeler crabs. Male red-line peelers experienced significantly longer times to molt when male crab density was high. Results of this study may lead to improvements in crab shedding technology, increased profits, and better fishery management practices.

BIOLOGICAL AND OPERATIONAL FACTORS CAUSING MORTALITY IN NORTH CAROLINA'S SOFT SHELL BLUE CRAB INDUSTRY

by

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Dedication

For my wife Rachel

No man could ask for more than what you have given me

Biography

I was born in Fredericksburg, Virginia, on July 26, 1969, the same day that the first men on the moon began their journey home. The next 18 years were spent in the small town of Falmouth, Virginia, where I learned to terrorize smallmouth bass, catfish, bluegills and striped bass on the Rappahanock River. My obsession with fishing began at the age of three. Summer vacations were spent in Nags Head, North Carolina as my fishing horizons expanded to include king mackerel, cobia, blue marlin, tuna, dolphin and wahoo. I began surfing the powerful waves of the Outer Banks at the age of 13 with my best friend David Loud.

In the fall of 1988 I began my Bachelors program at the Florida Institute of Technology, studying Aquaculture and Marine Biology. This program allowed me to travel to the Bahamas as a volunteer on a Nassau Grouper project with Dr. Jon Shenker. I fell in love with the Bahamas, and was fortunate to meet a young professor named David Eggleston who was looking for a summer technician. Luckily Dave hired me, allowing me to spend two consecutive summers on a tiny Bahamian island with less than 30 other people. This experience set me up for a Peace Corps Volunteer position as a Fisheries Research Officer on a small island in the South Pacific called Funafuti, the capitol of Tuvalu. Tuvalu is the second smallest country on Earth, made up of 9 tiny coral atolls that dot across 600 miles of ocean, with 10 square miles of total land area and a population of 10,000 people. The government's largest source of revenue has always been the sale of postage stamps.

Joining the Peace Corps was the most rewarding and interesting experience of my life. I learned to speak fluent Tuvaluan, dove with a whale shark, found a 50-year-old

American fighter plane on the bottom of the lagoon, was nearly killed three times, and almost got married at least once.

After the Peace Corps I returned to work in the Bahamas, saved money, and spent several months traveling throughout New Zealand and Fiji. My next job was as a fisheries observer in Alaska's Bering Sea and the Gulf of Alaska. On my first night in Alaskan waters, I stood at the galley window staring at the scene on deck for over an hour. 15-Foot waves crashed on the icy deck, snow flew sideways, and 800-pound fish traps swung over the heads of the fishermen like some giant death-pendulum. Walking out into that mess was the most dangerous thing I have ever had to do, every day for 6 months. When my contract was over, I got the hell out of Alaska, *fast*.

On September 20th, 1997, while working at the University of Miami, I began dating a Trinidadian woman named Rachel Wilson. We dated for several months before I said goodbye en route to Japan where employment awaited me. As I walked onto the airplane in Washington DC bound for San Francisco, my instincts told me that I was making a colossal mistake. I knew I couldn't leave Rachel, and walked off of the plane seconds before it left the gate. I called Rachel immediately and let her know my intentions.

We are now entering a fantastic 4th year of marriage, and are the proud parents of Eula (3 years) and Dominique (1 month). Dave Eggleston has been a constant mentor since 1990, and an overall positive force in my life since I began working with him. During the summer of 1999, Dave visited Rachel and I on the Eastern Shore of Virginia where I had grown tired of my job as the manager of a large aquaculture company. Dave's invitation to become a graduate student at NCSU in Raleigh was too good to refuse. The Egglestons welcomed us into their home in September of 1999 while I looked for a job and place to stay in Raleigh. Without the generosity of Dr. Eggleston and his family I would not be getting my masters degree now. Dave has shown me by his example how to be a great scientist, inspiring manager, and family man.

I currently enjoy writing songs, playing and recording music on several different instruments, and being on the water, either surfing, fishing, or kayaking. I thank God for the richest, happiest, most interesting life I could have ever imagined. All of my family and friends have been good to me and I will be forever indebted to them. After finishing my master's degree, I hope to get a novel published, the one that I wrote from 1995-1999 about my Peace Corps experience. My philosophy on life is simple: Do unto others as you would have them do unto you, work hard, and have as much fun as humanly possible.

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Introduction

Soft-shell blue crabs (*Callinectes sapidus)* are produced by aquaculture operations ("shedding operations") that hold premolt ("peeler") crabs until they molt (Ary and Poirrier 1989). Commercial fishermen sell soft-shell ("soft crabs") crabs for nearly 7 times more per pound than intermolt ("hard") crabs (Oesterling 1995). In North Carolina, the soft-shell crab industry has become an increasingly important component of the blue crab fishery, the state's most valuable fishery in terms of total landings, value, processing, participation, employment and amount of gear used (Henry and Mckenna 1998). Recently, a significant decline in the state's blue crab population and commercial landings (Eggleston et al. 2002, Eggleston et al. in prep.) has increased financial pressure on commercial fishermen, who look to production of soft crabs as a means of economic survival. Although most shedding operations are profitable, large financial losses are also common due to high mortality of peelers (Dell Newman, Commercial Fisherman, Swan Quarter, NC, pers.comm, Connie Ingraham, Crab shedding system operator, Wilmington NC pers.comm.). Thus, the value of the soft crab industry is directly dependent on mortality rate of peeler crabs. Several field and laboratory studies have documented the effects of water quality on crab survival and molting success (Ary and Poirrier 1989, Das and Stickle 1993, Lakshmi et al. 1984,Weis et al. 1992); however, no study has quantified mortality of peeler crabs in the soft crab industry, or identified sources of mortality. This study identifies and quantifies operational and biotic factors causing mortality in soft-shell shedding operations. This information should lead to improvements in shedding technology, better fishery management, and improved profits.

Blue Crab Biology

Unlike animals whose size increases on a continual daily basis, sub-adult and adult blue crab growth occurs in periodic steps that are spaced several months apart. The shedding of the old cuticle, termed ecdysis, occurs when crabs have spent several weeks secreting a new exoskeleton within the old one, then crack the sutures of the old shell and exit from inside with a new soft-shell that is larger than the old one. Four or 5 hours after molting, the soft-shell gradually hardens. When crabs begin to secrete their new shell, a white line becomes visible inside the cuticle of the crab's last appendage or swimmeret, which gradually becomes pink and then red. This line distinguishes a peeler crab from an intermolt crab and its color indicates the approximate time to molting. "White- line" peeler crabs are 3 weeks to 4 days from molting, and "red- line" peelers are less than 4 days from molting (Oesterling 1984).

North Carolina's Soft-Shell Blue Crab Fishery

Soft crab landings in North Carolina have made up 1.6% of the total blue crab landings for the past 8 years (~6,166,160 lbs.), but the value of this fishery has averaged 6.6% of the total during that same time, and increased to nearly 10% during 2001 (~ $3,336,990.) (NC Division of Marine Fisheries website, 2002). The increase in value of the soft crab fishery in North Carolina may be attributable to drastic declines in the blue crab population and in hard crab catch, and increasing local, regional, and worldwide demand (Oesterling, 1998).

In North Carolina, peeler crabs are trapped as by-catch in the hard crab fishery using hard crab pots or targeted directly using peeler pots. Hard crab pots are constructed of 3.8-cm wire mesh, fitted with at least 2 escape rings of 5.9-cm inside diameter (NC

Marine Fisheries Commission regulations 2002), and are baited with dead fish. Peeler pots are constructed of 2.54-cm mesh, and are not fitted with escape rings because there is no size limit on peeler crabs (NC Marine Fisheries Commission regulations 2002). Peeler pots are either unbaited or are baited with a mature male crab whose urine may attract pre-pubertal female peeler crabs (Ryan 1966). Pre-pubertal female peeler crabs are attracted to male blue crab urine because they are only able to copulate during a brief period of 2-3 hours after ecdysis. Finding a mate before molting is necessary to a female peeler crab's reproductive success.

Two types of shedding systems, open and closed, recirculating systems are used in North Carolina. In open systems, water is pumped into shedding tanks from a nearby source such as a creek or bay and drains back into the same water source. In closed systems, tanks are either filled with well water and aquarium salt added, or water is trucked in from the nearest suitable source. Water drains into a biological filter tank and is continuously pumped back into shedding tanks. Nitrogen fixing bacteria in filter tanks reduce the toxicity of ammonia in crab urine by reducing ammonia to nitrite and then to nitrate (Wheaton 1977).

Some operators of shedding systems believe mortality is caused by a variety of factors such as low dissolved oxygen, high temperatures, pesticide runoff, and injuries sustained from aggressive intermolt crabs in hard crab pots. Others believe male peeler mortality is high in the presence of female peelers whose sex pheromones may trigger reproductive behaviors that lead males to elevated stress and subsequent mortality during their molting process. Operators of shedding systems also feel that peelers sold by fishermen targeting hard crabs receive poor treatment after capture which causes high mortality. Such untested hypotheses are the basis of at least one current regulation in North Carolina which prohibits the possession of male white-line peelers after June 1st. Testing these hypotheses may lead to better fisheries management practices.

The overall objective of this study was to quantify biological and operational factors causing mortality in North Carolina's soft-shell crab industry. Specifically, we quantified the effects of 1) water quality on mean daily proportional crab mortality; 2) crab sex, crab size and molt stage on mean daily proportional mortality; 3) female crab presence or absence and molt stage on time-to-molt and survival of male crabs; 4) crab density on time-to-molt and survival of male crabs; and 5) crab source, system type, and gear used to catch peelers on mean daily proportional mortality.

Methods

Study Sites

Data were collected at eleven crab shedding systems throughout coastal North Carolina, USA (Fig.1) from May until October 2002. Sites were selected to represent a broad spectrum of water quality while simultaneously providing replicate closed and open systems (Table 1). Both large-scale seafood producers and small backyard operations were represented in this study. Seven sites used closed systems, three used open systems, and one site used both an open and a closed system.

Crab Collection

Crabs for the study were captured by commercial fishermen using hard crab and peeler crab pots. After capture, peeler crabs were stored in wooden baskets on the deck of a boat, or were placed in coolers on ice. Once landed at the dock crabs were placed in nearby shedding tanks, or trucked to shedding operations up to several hundred kilometers away.

Biological Considerations

At each of the 11 crab shedding study sites, pre-molt crabs were sexed and their carapace width measured (mm CW). Crabs were separated according to peeler stage (red line vs. white line) and then were equally distributed among four experimental tanks measuring 1.2-m wide x 2.4-m long and 20-cm deep.

Effects of water quality on crab mortality

To quantify the effects of water quality on crab mortality, the following water quality parameters were measured daily at ~ 0800 h; dissolved oxygen (mg/l), temperature (EC), salinity (parts per thousand; ppt), pH, and concentrations of nitrite (mg/l), nitrate (mg/l), and ammonia (mg/l). The response variable was mean daily proportional crab mortality. We used a weighted mean calculated from the number of crabs that died in each experimental tank per day divided by the number of crabs in the tank on that day. Tanks with red line crabs were monitored for 6d and tanks with white line crabs were monitored for 21d to allow crabs enough time to shed. If all crabs in a tank shed or died before the 6-or 21-day period, the experiment was terminated. The experimental unit was each tank, and four replicate tanks were used at each of 11 sites.

Dissolved oxygen and temperature were recorded using a YSI model 55 dissolved oxygen meter. Salinity was measured to the nearest 0.1 ppt using an optical refractometer. Nitrite, nitrate and ammonia were all measured using reagent test kits (Red Sea aquarium reagent test kits, Red Sea Fish Pharm Ltd. PO Box 4045, Eilat, 88000, Israel). PH was originally measured using Corning digital “Check Mite” pH meters (Mardel Co., Glendale Heights, Ill 60139), however litmus paper strips (Mardel Laboratories, inc 2656 West 240th street, Harbor City, CA, 90710) were used after digital pH meters malfunctioned.

To test for presence of pesticides in water of open systems, water samples were collected in experimental tanks before and after heavy rainfall events. Samples were collected on a day when it had not rained for at least 3 days and again approximately 1 hour after the start of a heavy rain. Samples were refrigerated and transported to the toxicology lab at North Carolina State University for analysis. Analyses of extracted samples (Mueller et al. 2000) were performed using an Agilent 6890 Series gas chromatograph and an Agilent 5973 Network Mass Spectrophotometer detector following the technique of Zuagg et al. (1998). Samples were analyzed for the following pesticides:

Herbicides: 2,6-diethylaniline, 2,6-diethylaniline, alachlor, atrazine, benfluralin, butylate, cyanazine, dacthal, desisopropylatrazine, ethalfluralin, metolachlor, metribuzin, molinate, napropamide, pebulate, pendimethalin, prometon, prometryne, simazine, tebuthiuron, and trifluralin.

Insecticides: carbaryl, carbofuran, chlorpyrifos, diazinon, disulfoton, ethoprop, flumetralin, fonofos, methyl parathion, permethrin, and terbufos

Others: chlorothalonil (fungicide), fenamiphos (nematocide), and tribufos (defoliant).

Statistical Analyses

In our initial visual examinations of the data and subsequent statistical analysis using a multiple regression model with crab source as a class variable, the source of crabs, whether purchased or self-caught, was the most important predictor of crab mortality. Thus, in all statistical analyses of the relationship between crab mortality and water quality parameters, we first divided the data into separate categories of self-caught versus purchased crabs so as not to confound mortality associated with the source of crabs with water quality parameters.

A backward, stepwise multiple regression model was used to examine the relationship between mortality rate of blue crabs and water quality parameters (DO, temp, salinity, pH, nitrite, nitrate, ammonia). Alpha to enter and remove factors from the model was 0.10. A Levene Median test (SigmaPlot 2001) tested for constant variance among the responses and a Kolmogorov-Smirnov test (SigmaPlot 2001) tested for normality. In cases where the data failed to meet the assumptions, the data were transformed using ArcSine or log10 transformations, which were successful in all cases.

Effects of crab sex, size, and peeler stage on crab mortality

To quantify the effects of crab sex and peeler stage on mortality, we compared the proportional mortality of male versus female crabs, and white line peelers versus red line peelers using ANCOVA with crab sex and peeler stage as factors and crab size as a covariate. We also tested whether or not the mean size of crabs initially placed in tanks differed significantly from the mean size of dead crabs using a one-way ANOVA. The data were normally distributed and variances were homogeneous.

Effects of female crab presence on mortality and time to molt in male crabs

Many shedding system operators believe sex pheromones given off by female peelers in shedding tanks causes male peelers to experience long times to molt and high mortality. We examined the effects of the female crab presence and molt stage on the time to molt and mortality of male crabs in a closed shedding system in Swan Quarter, NC. Twenty tanks, measuring 1.2-m wide X 2.4-m long and 20-cm high were filled with estuarine water from Albermarle sound to a height of 15 cm. Once the tanks were filled, the pump was turned off and water was not allowed to circulate between tanks, thereby preventing any potential pheromone contamination across tanks. Tanks were aerated by aquarium air pumps. Crabs were purchased from several fishermen and randomly assigned to one of three treatments that were systematically alternated between tanks during each experimental trial: 1) one red-line male per tank [control]; 2) one red-line male and one intermolt female per tank; 3) one red-line male and one red-line female per tank. These treatments would allow us to determine if the presence of a female crab increased a male peeler's time to molt and mortality.

We expected male red line peelers held with red line females to experience longer times to molt and higher mortality than those held alone or with an intermolt female. We did not expect any significant differences in time to molt or mortality for male red line peelers held alone or with an intermolt female. All crabs were visually examined hourly to record the time that they molted or died. When a red line male crab molted or died the trial was stopped. Each male red line peeler was an experimental unit and each treatment was replicated 7-9 times. The response variables were percent survival and time to molt in hours for male blue crabs.

Effects of increasing male crab density on mortality and time to molt of male crabs

A second experiment at Swan Quarter tested the effect of increasing male crab density in shedding tanks on percent mortality and time to molt in male crabs. This experiment was conducted because we felt that agonism among male crabs, or an interaction between male crab density and the presence of a red line female might delay male time to molt and increase mortality. Four treatments were systematically alternated among tanks: 1) One redline male per tank; 2) One redline male and one redline female per tank; 3) One redline male, one redline female, and one intermolt male per tank; 4) One redline male, one redline female, and three intermolt males per tank. These treatments were selected because we felt that they might reveal whether female pheromones, increasing male crab density, or both factors have a significant effect on male redline peeler time to molt and mortality. We expected male red line peelers would experience longer times to molt and higher mortality rates as male crab density increased, and expected no difference in time to molt and mortality when male red line peelers were held alone or with a single red line female. Each male red line peeler was an experimental unit and the response variables were time to molt and mortality. Each treatment was replicated 5-7 times.

Effects of crab sex on time to molt

In the third and final experiment, we quantified time to molt of male versus female crabs in the absence of other crabs to see if there was a sex effect that was independent of other factors. This experiment was conducted to determine if males simply took longer to shed than females regardless of any other factors such as presence of females or increasing crab density. Each tank contained a single male or female red-line crab. The response variable was time to molt in hours. Each crab was an experimental unit and each treatment was replicated 10 times.

Statistical analysis

The Lifetest procedure in SAS was used to compare the distribution of male's time to molt in the presence and absence of red-line females and other male crabs. The data was right censored (experiments ended before a response could be observed) due to the early termination of several trials when male crabs died before molting. The censored data points can not be left out of the analysis because crabs that take longer to molt are also more likely to die. The LIFETEST uses both censored and uncensored times to molt when comparing distributions of times to molt for various treatments. An uncensored data point is an actual observation of the time to molt, but the time to molt for censored data points is a calculation based on the distribution of times to molt among non-censored data points. Chi-Square tests were used to detect differences in mortality between treatments, and ANOVA was used to detect differences in the time to molt between male and female crabs.

Operational Considerations

Effects of shedding system, crab source, gear type and crab density on crab mortality

We compared mean daily crab proportional mortality in closed versus open systems, between self-caught versus purchased crabs, and between crabs caught in hard crab pots versus peeler pots with three separate one sample T-tests. We also examined the relationship between mean daily crab density and mean daily crab proportional mortality with a linear least squares regression model.

Results

Effects of water quality on crab mortality

The mortality rates of self-caught and purchased crabs did not vary significantly with any of the water quality parameters recorded (multiple regression; self-caught: all $p> 0.08$, purchased: all $p>0.16$).

Effects of crab sex, size, and peeler stage on crab mortality

Mortality rates of self-caught crabs were unaffected by sex and size (ANCOVA; sex: $F=3.06$, $df=1,20$, $p<0.10$; size: $F=3.03$, $df=1,20$, $p=0.101$) however self caught white line peelers did experience significantly higher mortality rates than self caught red-line peelers (ANCOVA; molt-stage: $F= 5.4$, $df=1,20$, $p= 0.034$; Fig 2a).

Mortality rates of purchased crabs were not affected by crab size (ANCOVA; $F=0.02$, $df=1,44$, $p=0.878$) however, purchased male peelers experienced significantly higher mortality rates than purchased female peelers (ANCOVA; $F=10.043$, $df=1,44$, $p< 0.01$; Fig 2b). It was not possible to determine the effect of crab stage on purchased crabs because there were no white-line peelers that were purchased. Crabbers who shed purchased peelers reported that if they bought white-line crabs, high mortality rates would cause them to lose money.

Effects of female crab presence and increasing male crab density on mortality and time to molt in male crabs

There was no difference in time to molt between males that were held alone, held with intermolt females, or held with red-line females (ANOVA; $F=0.13$; $df=3,23$; $p=0.718$;Fig 3a). There was also no difference in mortality between males that were held alone, held with intermolt females, or held with red-line females (Chi-square test;

x^2=4.1371, p=. 1264,df=1,44). In the second experiment that examined the effect of male density, time to molt was significantly shorter among males held with one red line female and one green male compared to the control group of males held alone (ANOVA; F=13.06; df=2,10; p=0.0056; Fig 3b). There were no other significant differences in time to molt among treatments (all p >0.07). There was no significant difference in mortality among conspecific treatments (Chi-square test; x^2=3.06, df=3,50,p=0.3819). In the last experiment that quantified male and female time to molt independent of other factors, male crabs time to molt was significantly shorter than female time to molt (ANOVA, F=14.21, df=1,19, p=0.0014, fig 3c).

Operational Considerations

Effects of shedding system, crab source, gear type and crab density on crab mortality

Shedding system type (i.e. open vs. closed) did not affect the mortality of self-caught crabs (t-test, t=1.23, df=1,48, p=0.22) or purchased crabs (t-test, t= 0.32, df=1,44, p=0.75). Mortality of blue crabs was significantly higher for purchased crabs than for self caught crabs (t-test; t= -2.22,df=1,50,p=0.03; fig 4). There was a significant inverse relationship between mortality of self-caught crabs and crab density (simple regression, F=14.2687 df=1,17 p=0.0016 Fig.5a.) The mortality rates of purchased crabs also decreased with increasing density, but this trend was only marginally significant (simple regression, F=4.05 df=1,19 p=0.0594 Fig.5b.) For self caught crabs, there was no difference in crab mortality between crabs caught by peeler pots or hard crab pots (peeler pots: 0 = 0.0244, se = 0.007, n=16; hard crab pots 0 = 0.03, se = 0.006, n=8; t=0.54, df=22, p= 0.60).

Discussion

This study quantified biotic and abiotic factors affecting mortality of blue crabs in North Carolina's soft-shell crab industry through collaboration with 11 different commercial crab operators spanning the entire state. We found that purchased crabs experienced significantly higher mortality rates than self-caught crabs. The majority of all peeler crabs in North Carolina shedding systems are purchased crabs (Tony Roughton, Seafood dealer and commercial fisherman, Columbia, NC, pers. comm.) and our data indicates that purchased peeler crab mortality is 11% greater than self caught crab mortality. The 11% difference in mortality rates of self caught and purchased peelers equates to a financial loss of over $776,044 per year for crab shedders alone. Disproportionately high mortality of purchased crabs can be eliminated by understanding the factors that cause purchased crab mortality to be greater than self-caught crab mortality. If the mortality rate of purchased crabs were reduced to that of self caught crabs, the soft crab industry would increase in value by 23% without any increases in harvest size. We are confident that mortality rates of purchased crabs can be reduced to the levels of self caugth-crabs through the collaboration of researchers, shedding system operators, and commercial fishermen.

Biological Considerations

Effects of water quality on crab mortality

Mortality rate of self-caught and purchased peeler crabs did not vary significantly according to any of the water quality parameters measured. Self-caught crabs appeared particularly resilient and were not affected by relatively high temperatures (17.4 – 31.8 EC), low dissolved oxygen levels (2.98 – 9.73 mg/l), or high nutrient loads (0 – 77.4

mg/l). Conversely, purchased peeler crabs appeared to be more vulnerable than self-caught peeler crabs, and experienced high mortality rates when oxygen was high, temperature was relatively normal, and nutrient concentrations were low. This result agrees with the opinions of many crabbers who feel that the way a crab is handled before it enters a shedding system is a greater determinant of crab survival than the quality of the water in shedding systems.

The contrasting results between our lack of pesticide effect on crab mortality and observations by crabbers of rainfall/pesticide spraying events that correspond to high mortality rates of crabs may be due to a lack of rainfall events occurring immediately after pesticide spraying events. A total of 5 out of the 33 pesticides that we tested for occurred in measurable concentrations (Atrazine, Metolachlor, Trifluralin, Diazinon, Carbofuran). These pesticides had no significant effect on crab mortality. Conversely, several shedding system operators in North Carolina have reported that when large rainfall events were preceded by pesticide spraying of nearby crops, crabs in their shedding systems suffered extremely high mortality rates (Bob Austin, Commercial Fisherman, Williston, NC, pers. comm.; Dell Newman, Commercial Fisherman, Swan Quarter, NC, pers. comm.; Russel Howell, Commercial Fisherman, Swansboro, NC, pers. comm.). Both open and closed systems are prone to these "pesticide/rainfall" mortality events because closed system operators usually perform frequent water changes and sometimes unknowingly re-fill their systems with contaminated water. Thus the use of pesticides in areas near crab shedding systems may represent a serious risk to peeler crabs in both open and closed systems alike, and warrants further study.

Effects of crab sex

Crab sex had a significant effect on the mortality of purchased crabs, but not on the mortality of self-caught crabs. Soft-shell shedding system operators who purchased crabs report that they always observed higher male mortality than female mortality, whereas operators who caught their own peelers reported that they never observed higher male mortality than female mortality. Several crabbers have suggested that high male mortality associated with purchased crabs is due to aggressive encounters that males experience in hard crab pots. We could not statistically test for a significant interaction between crab sex, crab source and gear type in a multiple linear regression model because nearly all purchased crabs were caught in hard crab pots, and nearly all self caught crabs were caught in peeler pots. Nevertheless, relatively high male crab mortality did coincide with the use of hard crab pots and not with peeler pots, suggesting a significant interaction between crab sex and gear type exists. Female peeler crab mortality may not be affected by the use of hard crab pots because female peeler crabs that enter hard crab pots are usually cradled with a pre-copulatory embrace by a male crab immediately after entry into a crab pot (pers. obs.). The male crab protects the female from other crabs and attempts to mate with her (Dell Newman, commercial fisherman, Swan Quarter, NC, pers. comm.). Alternatively, when a male peeler crab enters a hard crab pot, he is not protected from aggressive encounters with intermolt crabs, and may experience injuries or sub lethal stress that will not become manifest until he is placed in a shedding system and dies. In a peeler crab pot, intermolt crabs are rarely present, so males and females do not encounter aggressive intermolt crabs. Whether peeler crabs face sub-lethal aggressive encounters with aggressive intermolt crabs in hard crab pots is unknown, but further research in this area may explain the sex effect among purchased peelers.

Effects of crab stage

Mortality of self-caught white line peelers was significantly higher than the mortality of self caught red line peelers. We were unable to analyze the effect of molt stage on purchased peelers because shedding system operators do not attempt to shed white line peelers for fear of high mortality rates. White line peelers probably experienced higher mortality rates because of long periods of time required for them to molt, in which they are more likely to suffer from accumulated stress. The peeler crab fishery is regulated on the assumption that male white line peeler mortality is very high during summer months, and that to keep them would be a wasteful practice. It is therefore illegal to possess white line male peeler crabs after June 1st. Although our results agree in part with this assumption, it is important to note that the mortality of self caught white line peelers is still lower than the mortality of purchased red line peelers, implying crab source as a more significant determinant of crab mortality than molt stage.

Effects of crab size

We failed to detect any effect of crab size on crab mortality rates, contrary to popular belief that male peeler crab mortality increases with crab size, especially when males become very large. There may not have been enough contrast in our data to reveal a positive relationship between crab size and mortality since male peelers >16mm CW were rarely observed. The belief among crabbers that male peelers experience high mortality is so prevalent that many have given large male soft-shell crabs the nickname “miracle crabs.”

Effect of female crab presence and increasing male density on mortality and time to molt in male crabs

Male red line peelers held with a low density of intermolt male crabs experienced significantly shorter times to molt than control crabs, but time to molt did not differ significantly between male red line peelers held with a high density of intermolt males and the control crabs. This result was contrary to the expected result that increasing male density would cause longer times to molt, and is probably due to chance rather than any biological phenomenon.

Male red line peelers experienced significantly shorter times to molt than female red line peelers, contrary to our expectation that time to molt would be equal among males and females or that males might experience longer times to molt than females. Similarly, Hunt and Lyons (1986) found shorter intermolt periods among male than female adult Caribbean spiny lobsters (*Panulirus argus),* another decapod crustacean. Our findings differ from the opinions of many crabbers who believe that male red line peeler crabs in shedding tanks take longer on average to molt than female red line peeler crabs. Further investigation might reveal the extent to which intermolt periods differ between male and female blue crabs. In our experiments, male peeler crabs showed no ability to regulate their time-to-molt in response to different situations (i.e. the presence of red- line female, different levels of conspecific density).

Operational Considerations

Effects of crab source and crab density on crab mortality

Crab source was always the single greatest source of variation in crab mortality rates. Variability in mortality due to crab source is likely caused by different handling methods used by crabbers who shed their own peelers versus crabbers who sell peelers. Crabbers who shed their own peelers put forth great effort to ensure the survival of their peeler crabs, such as carrying a cooler with ice and wet burlap bags in their boats, which keep crabs cool and moist. Crabbers who sell peelers usually place peeler crabs in a wooden basket on the deck of their boat, unprotected from bright sun, wind, and extreme heat. Purchased peeler crabs may also experience significantly higher mortality rates than self caught peelers because they are more likely to travel great distances from the point of capture to shedding systems. Long travel times may cause crabs to dehydrate, but also increase the likelihood that crabs will experience large changes in salinity from the point of capture to shedding tanks. Although blue crabs are euryhaline organisms that can survive in a broad range of salinities from 0 ppt to over 40 ppt, sudden large changes in salinity (i.e., > 10 ppt in less than 24h.) may exceed a crab's ability to osmoregulate the tissues in its body, causing mortality (Engel and Thayer, 1998). Although we were unable to record changes in salinity from the point of capture to a given shedding system, these salinity changes may explain why mortality of purchased peelers was significantly greater than mortality of self-caught peelers and is worthy of further research. A crabber who sells these peelers is unaffected by high mortality rates that may occur in shedding systems because market demand for peeler crabs insures that they will receive top dollar for these peelers, despite their relatively poor treatment.

Mortality of both self-caught and purchased crabs decreased as crab density increased. It is possible that crabs abandon aggressive behavior that causes mortality once density has increased to a certain level, as evidenced by some species of fish that abandon territorial behavior if density surpasses a certain threshold (Dr. Jon Shenker, pers.

comm.). Many operators feel that peelers can be stocked at extremely high densities (>250 crabs/tank) without any harmful effects as long as good aeration is maintained in the tanks and all crabs placed in the tank are red line peelers. Failure to carefully examine the molt stage of each crab placed in tanks allows the accidental entry of both intermolt and white line peelers, which are known to cannibalize red line peelers.

Isolating crabs from each other may be a highly effective method of reducing crab mortality. One of the sites in this study reduced mortality in his system several years ago by placing 100 plastic mesh cylinders in each tank to isolate crabs from each other. The cylinders were originally designed to eliminate cannibalism, but the operator felt that the reduction in mortality he observed was significantly larger than that caused by cannibalism alone. The cylinders were used at his site during this study, and the resulting mortality was consistently the lowest in the entire state. Eliminating physical interaction between crabs may greatly reduce crab stress, and therefore reduce mortality. Most operators are reluctant to try isolating crabs in tanks because they feel that cylinders would greatly reduce the capacity of shedding tanks during large runs of peeler crabs when tanks are stocked at densities of 200-300 crabs. These peeler runs only occur two or three times each year, however, and it is not likely that peeler supply would exceed the capacity of 100 crabs per tank during the rest of the shedding season.

Our study revealed sources of mortality in the NC soft-shell crab industry that fisherman are capable of eliminating. The survival of self-caught peeler crabs is significantly higher than for purchased crabs. Implementing regulation changes in the soft crab industry could force crabbers to consider three new options in the place of selling peelers that have been poorly treated: A) take better care of peeler crabs by always placing them in a cooler on ice immediately after capture or underneath wet burlap sacks; B) Sell peeler crabs larger than 12.7 cm CW as hard crabs; C) or release peelers unharmed if they are smaller than 12.7 cm CW. Benefits of new regulations will likely include a reduction in the mortality rate of peeler crabs in shedding systems, increased financial profits for crabbers who sell peelers that are now more likely to survive in shedding systems, improved profits of shedding system operators who purchase peeler crabs, and reduced fishing pressure on sub-legal sized peeler crabs.

REFERENCES

Ary, Roy D, Jr., and Michael A Poirrier 1989. Acute Toxicity of Nitrite to the Blue Crab (Callinectes sapidus). The Progressive Fish Culturist 51: 69-72.

Christy, J. H. 1987. Competitive mating, mate choice, and mating associations of brachyuran crabs. Bulletin of Marine Science 41: 177-191.

Cowan, D. F. 1991. The Role of Olfaction in Courtship Behavior of the American Lobster *Homarus americanus*. Biological Bulletin 181: 402-407.

Cronin, L. E. 1998. Early days of crabbing and a brief history for the Chesapeake Bay. Journal of Shellfish Research 17(2): 379-381.

Das, Tapash, and William B. Stickle (1993). Sensitivity of Crabs Callinectes sapidus and C. similis and the gastropod *Stramonita haemastoma* to hypoxia and anoxia. Marine Ecology Progress Series 98: 263-274.

Diesel, R. 1988. Male–female association in the spider crab *Inachus phalangium*: The influence of female reproductive stage and size. Journal of Crustacean Biology 8: 63-69.

Eggleston, D.B., Joseph Hightower and Eric Johnson 2002 Population dynamics of the Blue Crab *Callinectes sapidus* in North Carolina. Fishery Resource Grant report 99FEG-10 and 00-FEG-11

Guillory, Vincent, and Stephen Hein 1998. A review and evaluation of escape rings in blue crab traps. Journal of Shellfish Research 17(2): 551-559.

Manthe, Don P, Ronald F. Malone and Sunil Kumar 1988. Submerged rock filter evaluation using an oxygen consumption criterion for closed recirculating systems. Aquaculture Engineering 7: 97-111.

Mueller, J.F., Duquesne, S., Ng,J., Shaw, G.R., Krrisnamohan, K., Manonmanii, K., Hodge, M., Eaglesham, G.K., 2000 Pesticides in sediments from Queensland irrigation channels and drains. Marine Pollution Bulletin, 41(7-12) (294-301)

Henry, Lynn T. and Sean McKenna 1998. Status and Management of the Blue Crab Fishery in North Carolina. Journal of Shellfish Research 17(2): 465-468.

Hunt, John H. and William G. Lyons 1986. Factors affecting growth and maturation of spiny lobsters, *Panulirus argus*, in the Florida Keys. Canadian Journal of Aquatic Sciences, 43: 2243-2247

Lakshmi, G.J., C. M. Trigg, H.M. Perry,and A. Venkataramiah. 1984.The effects of ammonia accumulation on blue crab shedding success. Mississippi-Alabama Sea-Grant Consortium, Project R/RD-2, Ocean Springs, Mississippi.

Lipscius, R.N. and W.F Herrnkind 1982. Molt cycle alterations in behavior, feeding and diel rhythyms of a decapod crustacean, the spiny lobster *Panulirus argus.* Marine Biology 68, 241-252

Oesterling, M. 1984. Manual for handling and shedding blue crabs (*Callinectes sapidus)*. Institute of Marine Science, College of William and Mary, Special Report 271, Gloucester Point, Virginia.

Oesterling, M. 1995. The Soft Crab Fishery. Virginia Marine Resource Bulletin 27(1-2): 13-14.

Oesterling, M. J. 1998. "Blue" crab resources in other countries: Implications for the US industry." Journal of Shellfish Research 17(2): 375-378.

Prejean, Paul, and Vincent Guillory 1998. An evaluation of small mesh baited traps for peeler crab capture. Journal of Shellfish Research 17(2): 563-565.

Ryan, E. P. 1996. Pheromone: Evidence in a Decapod Crustacean. Science 151,no.3708, (340-341.)

Tagatz, M. E. (1968). Biology of the blue crab, *Callinectes sapidus* Rathbun, in the St. John's River, Florida. Fishery Bulletin 67(1): 17-33.

Thayer, D. W. E. a. G. W. (1998). Effects of habitat alteration on blue crabs. Journal of Shellfish Research 17(2): 579-585.

Wheaton, F.W. 1977. Aquacultural engineering. Wiley-Interscience, New York.

Webster, D. (1998). Soft Crabs and recirculating systems. Aquaculture: 23-24.

Weis, Judith S, Angela Cristini, and K. Ranga Rao (1992). Effects of Pollutants on Molting and regeneration in Crustacea. American Zoology 32: 495-500.

Zuagg, S.A., Barber, L.B., Brown, G.K., Writer, J.H., 1998 Analysis of potential endocrine disrupting chemicals in sewage effluents by continuos liquid-liquid extraction, derivization and gas chromatography/mass spectrometry. American Chemical Society, World Meeting (983-0101)

Table 1. List of shedding operations, locations, system type, source, and months of trials

Crabber	Location	System type	Source	Dates of Trials	n
Austin	Williston	Open	Self-Caught	May	1
Bridges	Collington	Closed	Purchased	August-October	3
Howell	Pettiford Creek	Open and Closed	Self-Caught and purchased	May-September	5
Ingraham	Wilmington	Open	Purchased	May-July	3
Klotz	Bayboro	Closed	Purchased	May-August	4
Mason	Swan Quarter	Closed	Self-Caught	August	1
Newman	Swan Quarter	Closed	Purchased	June-September	4
Phillips	Columbia	Open	Purchased	June- October	5
Rader	Wilmington	Closed	Self-Caught	May, July-October	5
Roughton	Columbia	Closed	Purchased and Self-Caught	May, June, August	3
Smith	Wilmington	Closed	Self-Caught	May-July	3

Table 2. Ranges and means of water quality parameters measured.

Factor	Range	Mean
Temperature	17.4-31.8 C	25.6 +- 0.4 C
Dissolved Oxygen	2.98-9.73 mg/l	6.18 +- 0.24 mg/l
Salinity	3.7-39.8 ppt	19.1 +- 1.7 ppt
Nitrite	0-0.5 mg/l	0.2 +- 0.02 mg/l
Nitrate	0-77.4 mg/l	17.2 +- 2.7 mg/l
Ammonia	0.1-3.5 mg/l	0.6 +- 0.1 mg/l
pH	5.5-8.0	7.3 +- 0.07

Table 3. Results of multiple linear regression analysis of water quality parameters on the mortality rates of self-caught peeler crabs.

Factor	F	P
Temperature	0.58	0.4633
Dissolved Oxygen	0.94	0.3525
Salinity	<0.01	0.9534
Nitrite	1.34	0.2707
Nitrate	1.21	0.2955
Ammonia	0.1	0.7552
pH	1.89	0.1968

Table 4. Results of multiple linear regression analysis of water quality parameters on the mortality rates of purchased peeler crabs.

Factor	F	P
Temperature	1.2	0.294
Dissolved Oxygen	<0.01	0.962
Salinity	0.38	0.5472
Nitrite	1.08	0.3173
Nitrate	1.78	0.2051
Ammonia	2.6	0.1311
pH	3.75	0.075

FIGURE LEGEND

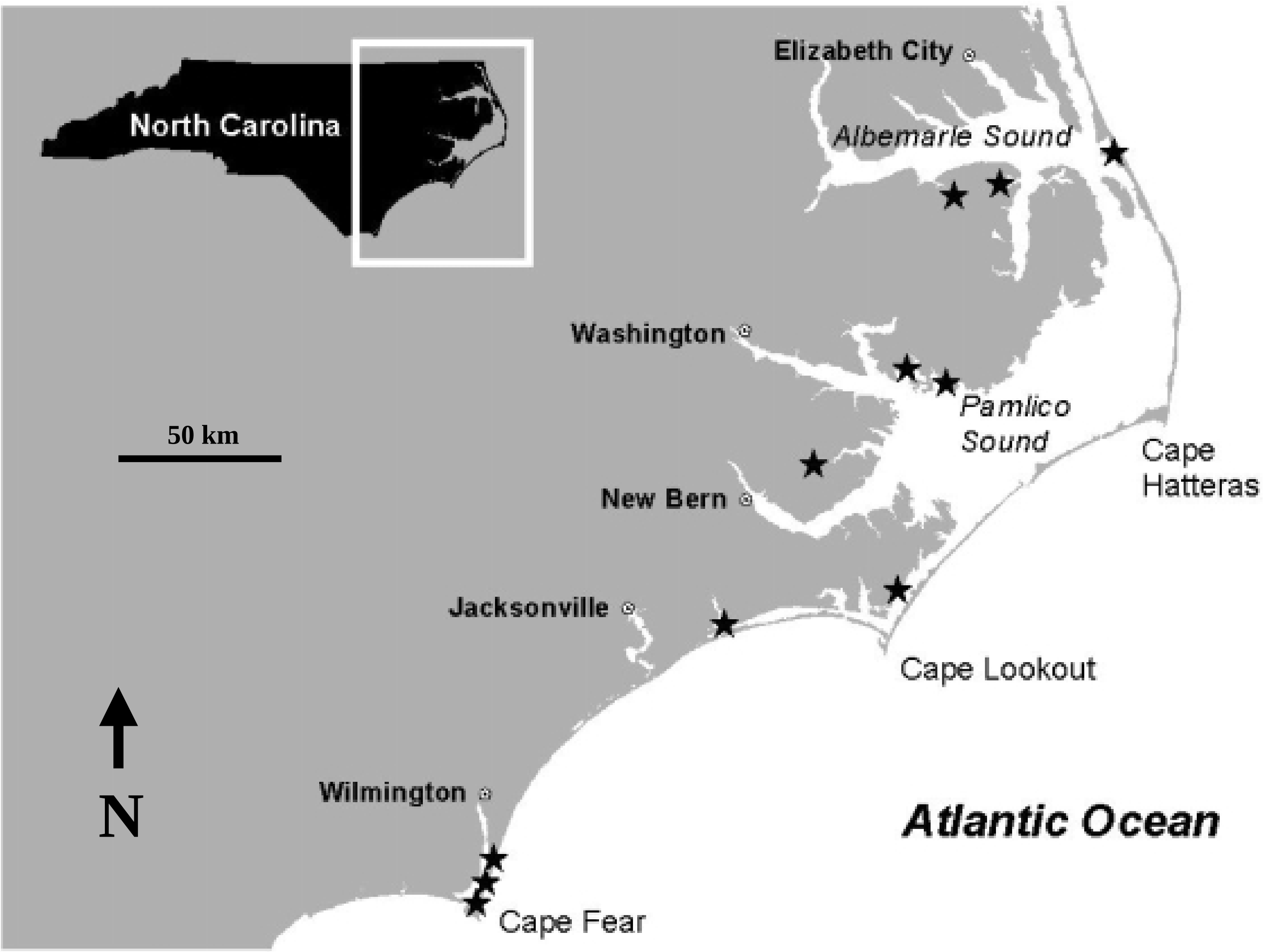
Figure 1. Map of North Carolina showing locations of study sites.

Figure 2. Mean daily proportional mortality of self-caught white-line versus red-line peeler crabs (a); and mean daily proportional mortality of purchased male versus female peeler crabs. Means (∀SE) of each group are plotted.

Figure 3. Male red-line peeler time-to-molt in hours when held alone (control), with an intermolt female, and with a red-line peeler female (a); Male red-line peeler time to molt when held alone, with one red-line female, with one red-line female and one intermolt male, and with one red-line female and three intermolt males (b); and time-to-molt of male red-line peelers held alone and female red-line peelers held alone.

Figure 4. Mean daily proportional mortality of self-caught versus purchased peelers.

Figure 5. Mean daily proportional mortality of self- caught peelers versus density (a); and mean daily proportional mortality of purchased peelers versus density (b)



North Carolina
Elizabeth City
Albemarle Sound
Washington
Pamlico
Sound
Cape
Hatteras
50 km
New Bern
Jacksonville
Cape Lookout
Wilmington
N
Atlantic Ocean
Cape Fear

Figure 1

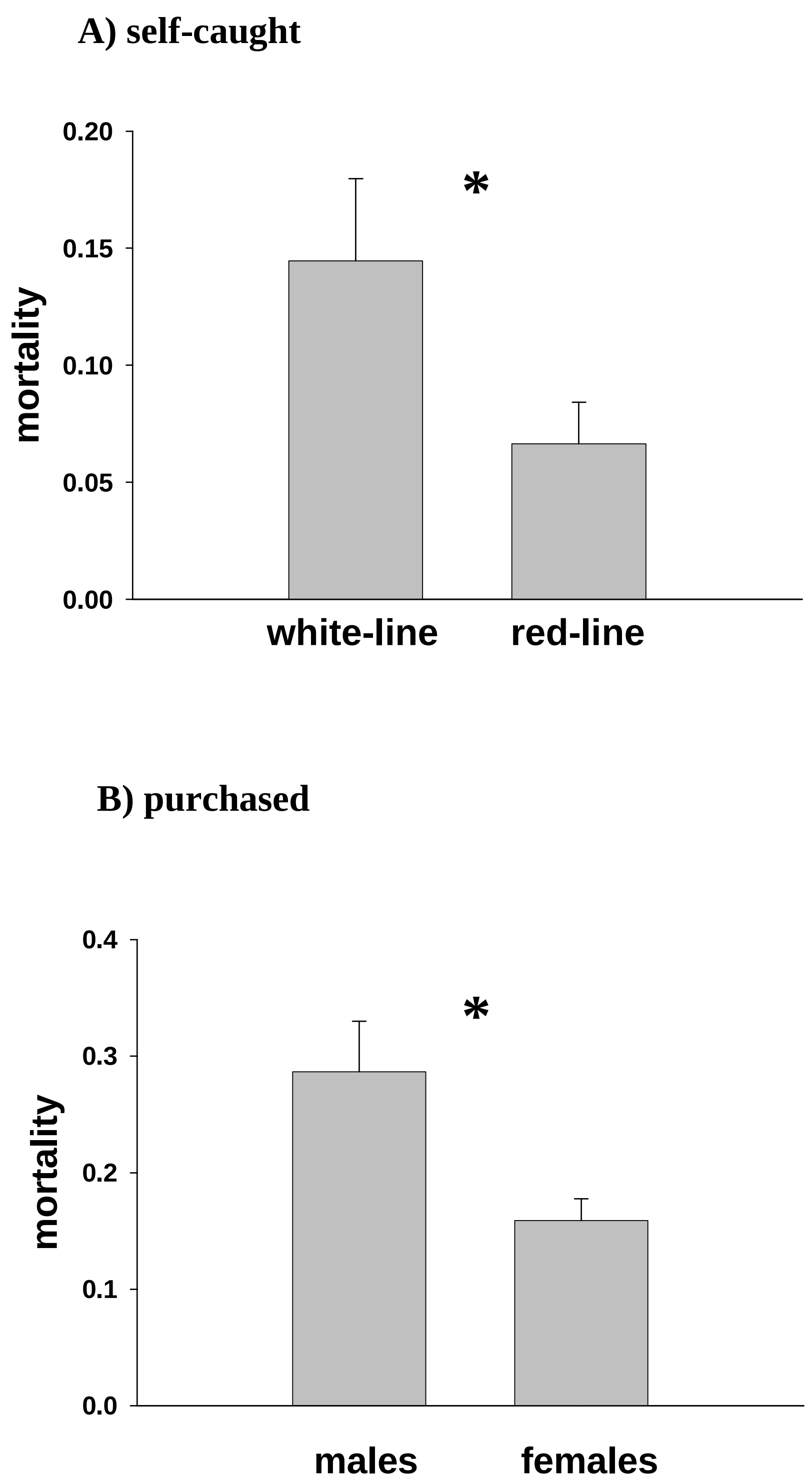
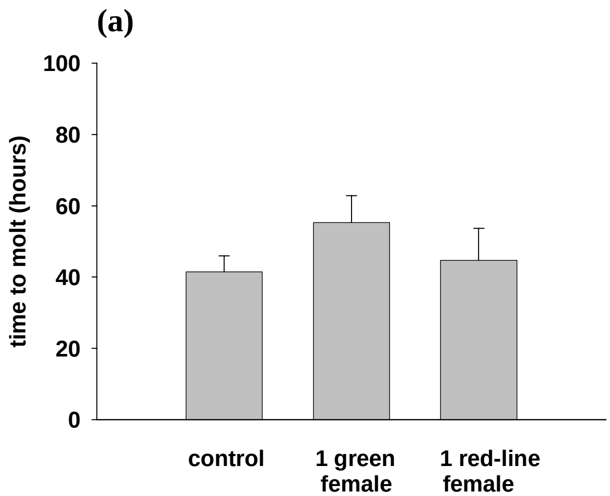
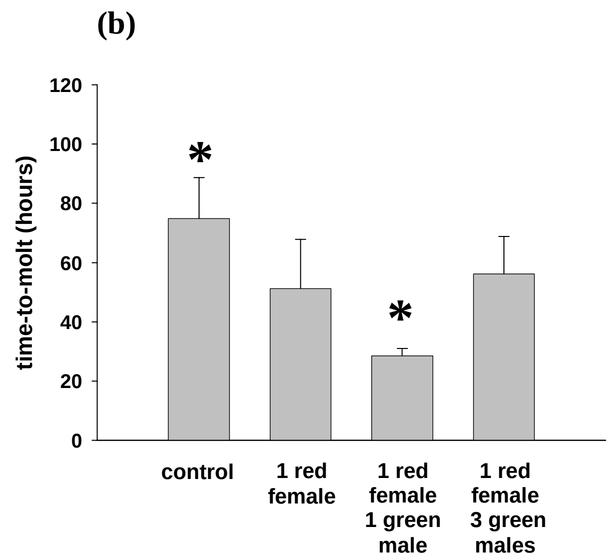

A) self-caught
mortality
0.20
0.15
0.10
0.05
0.00
*
white-line
red-line
B) purchased
mortality
0.4
0.3
0.2
0.1
0.0
*
males
females

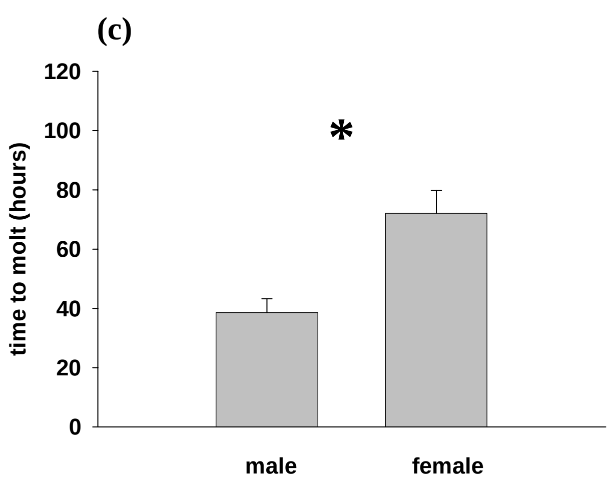
Figure 2



(a)
time to molt (hours)
100
80
60
40
20
0
control
1 green female
1 red-line female



(b)
time-to-molt (hours)
120
100
80
60
40
20
0
*
*
control
1 red female
1 red female 1 green male
1 red female 3 green males



(c)
time to molt (hours)
120
100
80
60
40
20
0
*
male
female

Figure 3

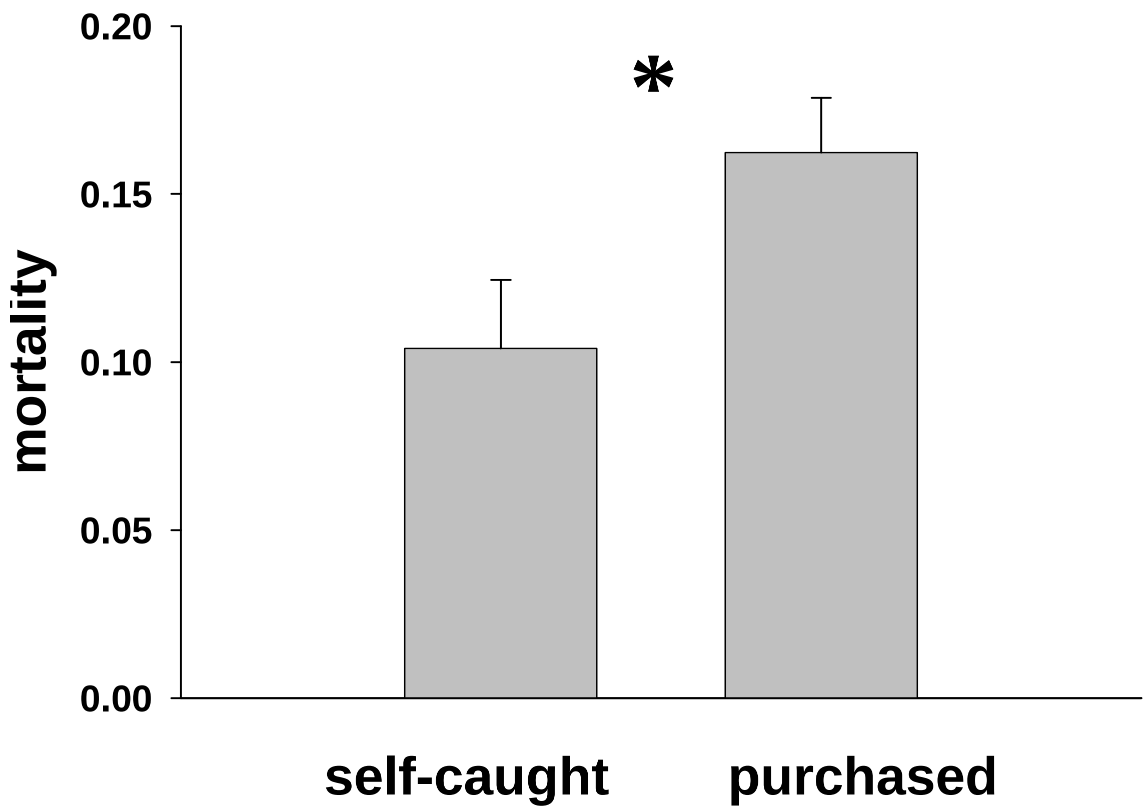
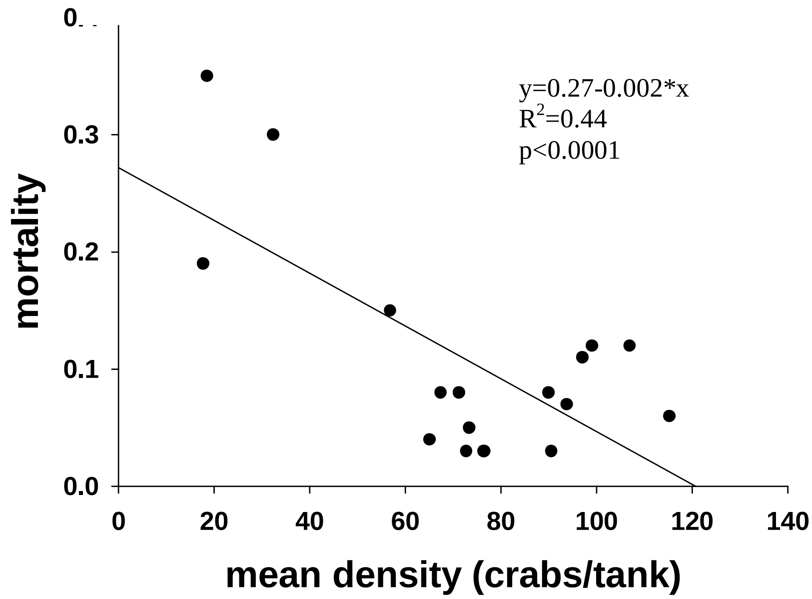


Figure 4

A) self-caught



B) purchased

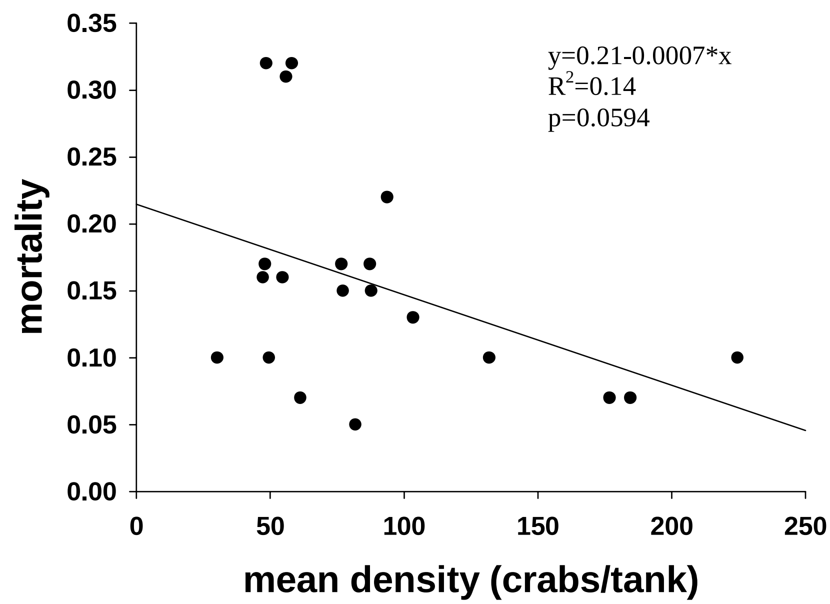


Figure 5