The Effectiveness of Rotating Marine Protected Areas (MPAs) in Fisheries Management: A Case Study of the NC Hard Clam Fishery

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Curriculum in Ecology.

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ABSTRACT
Eileen M. McDaniel: The Effectiveness of Rotating Marine Protected Areas
(MPAs) in Fisheries Management: A Case Study of the NC Hard Clam Fishery
(Under the direction of Charles Peterson)

For successful conservation, traditional fisheries management such as
restrictions on gear and catch size must be combined with the designation of
Marine Protected Areas, or MPAs. Scientific research has demonstrated that
MPAs have restored populations of fish and shellfish that they protect. Because
permanently closing off areas to harvest is likely to be contested by user groups,
MPAs that are temporally and spatially rotated are more practical than
permanent closures, because the boundaries are more likely to be respected, yet
biological benefits still can be achieved. I have performed a fishery-independent
study to evaluate the success of a management strategy implemented by the
North Carolina Division of Marine Fisheries in the hard clam (*Mercenaria
mercenaria*) fishery in Carteret County, NC, in which MPAs were rotated between
Core and Pamlico Sounds. Clam harvesting is efficiently performed in this area
by a unique mechanical technique called "clam kicking".

The clam kicking rotation plan was a successful management strategy for
the hard clam fishery in the study area. Rotating MPAs was more acceptable to
fishermen because they were opposed to permanently relinquishing valuable
clamming grounds. The trade-off of opening a previously closed area in Pamlico

Sound with closing the historically productive but overharvested area in Core

Sound was effective in not only increasing clam abundances in the newly

protected area in Core Sound, but also in increasing the overall productivity of

the fishery. From 2001 to 2003, overall productivity of the fishery in Core and

Pamlico Sounds increased by 70%, while the productivity of the state fishery

declined by at least 30%.

DEDICATION

I'd like to thank my wonderful husband Stephen, for his never-ending patience in listening to me talk about the fascinating world of the hard clam! Now that you're done with your book and I'm done with my dissertation we will actually have free time!

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure

INTRODUCTION

Fishing has become a global business enterprise that is vital to the global economy (Pauly *et al.* 2005). For example, the international value of fisheries production reached US $58.2 billion in 2002 (SOFIA 2004). However, supplies of this valuable commodity have been decreasing over time. Although demand has remained relatively stable, the total production of marine capture fisheries has decreased from a peak of 86.8 million tonnes in 2000 to 81.3 million tonnes in 2003 (SOFIA 2004). The worldwide decline in the harvesting of marine products was ultimately caused by advances in procurement technology and techniques. According to Jackson *et al.* (2001), technological advances resulted in large fishing vessels that were able to harvest in previously inaccessible waters as well as efficiently capture large marine animals. During the last century, the populations of many marine species plummeted.

In 1982, these technological advances in vessels and gears combined with a new United Nations policy regarding international waters led to further declines in fish populations. Traditionally, waters that were three nautical miles from a country's coastline belonged to that country. Beyond three miles were international waters, open to all nations. The United Nations Convention on Law of the Sea recognized the right of a country to claim Exclusive Economic Zones (EEZs) in which it could exclusively exploit natural resources such as oil and

fisheries extending to distances of two hundred nautical miles from the coastline.

Although on the surface it appears that EEZs would help countries protect their marine resources, in reality they were devastating for commercially fished species. Instead of tightly regulating fishing, global competition combined with grossly overestimated projected fishery yields pushed countries to overfish, providing little incentive to protect fisheries. Initially, catches increased (partially due to the exploitation of previously unfished deep water stocks), but then started to decrease in the late 1980's (Pauly *et al.* 2005).

The worldwide collapse of fisheries and the resulting social and ecological effects have demonstrated that traditional fisheries management is insufficient. National governments support overcapitalization of fishing fleets, resulting in overexploitation (Hilborn *et al.* 2005). Countries must decrease the size of their collective fleets by eliminating subsidies to fishing (Pauly *et al.* 2005). In maritime nations, there are numerous flawed policies at the regional and state levels as well, including management agencies allowing open access to fishing grounds, failing to enforce regulations, and running fisheries by consensus of fishers (Hilborn *et al.* 2005). Fisheries usually are managed as a single species, and the effects on other species and the entire ecosystem are not measured (Pauly *et al.* 2005). Rules consisting simply of gear restrictions, catch size, and catch reduction are insufficient. To restore ecosystems and fisheries, the spatial refugia that occurred naturally before vessels could access virtually every species and depth must be re-established (Pauly *et al.* 2005).

Spatial refugia in the ocean are termed Marine Protected Areas (MPAs). MPAs are defined by the World Conservation Union as "any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment" (Kelleher *et al.* 1991). While terrestrial protected areas have existed since the nineteenth century, the use of MPAs has been relatively recent, starting in the early 1980's. They usually are created for the purposes of biodiversity conservation and/or fisheries management, although this research focuses on the fisheries management aspect. The majority of studies to date indicate that MPAs are successful in restoring populations, at least within the MPA boundaries (Halpern and Werner 2002).

Recent scientific debate addresses the establishment of MPAs versus marine reserves, a type of MPA that is fully protected and prohibits removal of all organisms. Lubchenco *et al*. (2003) argue that marine reserves provide more benefits than MPAs. While it is difficult to refute the idea that a fully closed area protects wildlife better than a partially closed one, in reality marine reserves may not be a viable option. Fishers often disagree with the use of marine reserves due to the fear of permanently losing valuable fishing grounds (Rieser 2000). The success of the reserve in increasing abundances and biomass of the targeted fish is coupled to fisher compliance in respecting the reserve boundaries (Roberts 2000). Since fishers cannot always be monitored, it is crucial to have their support to reduce illegal fishing. Therefore environmental managers must

realize that economics or politics may prevent a solution that is biologically optimal from being implemented and be willing to compromise (Possingham *et al.* 2000).

There is a realistic solution to the problem of balancing the needs and compliance of fishers with biological constraints in restoring target populations: the temporal and/or spatial rotation of MPAs. The rotation of MPAs is quite rare, so I have taken advantage of an opportunity that occurred on the central North Carolina coast to study the effectiveness of rotating MPAs in the management of the hard clam (*Mercenaria mercenaria*) fishery. This fishery is vital to both the local and state economies and traditionally has been more productive than in the present day. Chapters 1, 2 and 3 of my dissertation investigate the hard clam harvesting rotation plan that was implemented in 2001 by the North Carolina Division of Marine Fisheries. An overharvested yet historically productive clamming area was closed and a new unharvested area was opened for a period of two years in order to increase productivity of the fishery, and then the original clamming grounds were restored.

In Chapter 1, I focus on the effects of rotating MPAs on the productivity of the hard clam fishery in the study area in Core and Pamlico Sounds, Carteret County, NC. I elaborate on the marine management context, case study and research design. Then I utilize my fishery-independent dataset to calculate clam abundances, develop models to describe changes in the clam populations during the course of the rotation, and compare my data to state commercial clam landings. In Chapter 2, I explore the changes that occurred in seagrass

populations, a valuable habitat for fish and shellfish including hard clams, in the study areas coinciding with the rotation plan. In Chapter 3, I investigate the changes in size distributions in clam populations as they are exposed to or protected from harvesting as a result of the rotating MPAs.

Additionally, I completed a second project that consisted of determining if a "clam lease", a large area of estuarine bottom leased out to a local fisherman for aquaculture purposes, supplements the wild clam population in the surrounding areas opened to clamming by exporting larvae. In Chapter 4, I summarize the results of the clam lease project.

PROJECT SIGNIFICANCE

The consequences of overfishing are potentially devastating both socially and ecologically. Marine production is crucial to providing nutritional sustenance to human populations. Worldwide, fish and shellfish supply approximately sixteen percent of total animal protein to human diets (SOFIA 2004). In developing countries, per capita fish supply has declined due to the operation of the global fish market. Many poor countries have sold fishing rights to other countries or heavily export valuable fish to pay off debts. These actions have resulted in a shortage of seafood for local fishers to catch for either sustenance or sale (Pauly *et al.* 2005). Although approximately 70% of global fisheries production is consumed by humans, a portion of the remainder is used to feed domesticated animals that humans consume (Garcia and Grainger 2005). This additional trophic level wastes energy and protein. Ironically, aquaculture also may

contribute to the shortage of fish available for human consumption as fishmeal is often fed to the stocks (Pauly *et al.* 2005). Additionally, thirty-eight million people worldwide are directly employed in fishing activities for their livelihoods (SOFIA 2004).

There are many negative repercussions of overfishing on the environment at multiple scales. Lubchenco *et al.* (2003) listed the aspects of ecosystem structure that are affected by fishing. These include species diversity, population abundance, size structure, sex ratios, behavior, habitat structure, trophic dynamics, biogeochemistry, and biological interactions.

Chapter 1.
The effects of rotating Marine Protected Areas (MPAs) on the productivity of the North Carolina hard clam (*Mercenaria mercenaria*) fishery.

INTRODUCTION

The overexploitation and collapse of fisheries worldwide have demonstrated that conventional fisheries management is inadequate and must be combined with Marine Protected Areas or MPAs (Pauly *et al.* 2002). The term MPA encompasses marine reserves, marine preserves, fishery reserves, ecological reserves, and marine sanctuaries, most of which lack standardized definitions (except for marine reserves, which generally are completely closed to fishing). MPAs may be useful in both the recovery of exploited species and the maintenance of harvests. They function by protecting important habitat, enhancing recovery of populations of fished species thereby increasing spawning stock biomass, causing spillover or movement of juveniles and adults into open areas, exporting larvae into open areas and protecting against uncertainties (Rieser 2000, Lubchenco *et al.* 2003). Currently, MPAs protect less than one percent of the world's oceans.

The creation of marine reserves is an ecosystem-based method (Botsford *et al.* 1997) of fisheries management. Ecosystem-based management may aid in the protection or restoration of fisheries by conserving or re-establishing the structure

and function of the ecosystems within which they exist (Pauly 2003). Marine reserves decrease mortality of fish populations and prevent destruction of important habitat resulting in increased population abundances, individual fish size, productivity of marine life and habitat structure (Lubchenco *et al.* 2003). Fisheries goals of marine reserves include maintaining yields and creating a buffer against miscalculations of management (Roberts *et al.* 2003). Scientific research regarding the effectiveness of MPAs suggests that they have accomplished some of these goals. Halpern and Warner (2002) evaluated 112 studies of 80 reserves in which both fish and invertebrates from all trophic levels were evaluated. All of the studies focused on either less than five or more than fifty species. Comparing areas within the reserve boundaries to outside, they found that mean values of population densities were 91% higher, biomass was 192% higher and organism size and diversity were 20% to 30% higher. These results were independent of reserve size and significant increases occurred within one to three years.

The consensus among scientists can be summed up by Roberts *et al.* (2005) who state that traditional fisheries management methods can complement MPAs but cannot be effective without them. Marine reserves must be used to replenish fisheries, protect non-target species and restore ecosystem function. It is biologically ideal to establish a fully protected, permanent marine reserve where no extractive activities are allowed, because the fish and shellfish populations most likely would experience the benefits previously discussed including higher population densities, biomass and species diversity. However,

fishermen are strongly opposed to permanently relinquishing fishing grounds, especially if there is no definitive proof that the areas that remain open will benefit from the closed area because of spillover or protection of spawning adults leading to increased larval export.

MPAs that are temporally and/or spatially rotated are more practical than permanent marine reserves because of their greater acceptance by user groups. Fishermen are more willing to temporarily sacrifice fishing grounds because they have a specific date when they will be re-opened. If the fishermen are allowed to fish in a re-opened MPA that scientists have determined has successfully restored fish populations, the fishermen have a chance to experience firsthand the benefits of the MPA. Perceptions of user groups, especially commercial fishermen, regarding the usefulness of an MPA is vital to its success. Usually law enforcement can not be a constant presence in protecting the boundaries of the MPA due to monetary restrictions, so user groups must be, at least to a certain extent, willing participants.

Rotation of MPAs

A rotating spatial harvest (RSH) is a variation of a permanent marine reserve in which the harvest region is divided into areas that are opened and closed on a rotating basis for a certain number of years (Gerber *et al.* 2003). The authors analyzed 34 papers that modeled marine reserves and found only six models that considered harvest rotation. They recommended that future modeling include RSH as a management alternative. Additionally, models must be

updated with empirical data from reserves in order to provide useful information

(NRC 1999). In his review on the efficacy of marine reserves, Halpern (2003)

found that only a few studies sampled more than one time, had before and after

data, and collected data inside and outside the MPA boundaries. Virtually all the

studies were done near coral reefs, rocky shores or intertidal zones (Halpern

2003) so data on soft-bottom habitats are rare. There are few studies done on

how the reserve affects fish populations and habitats in outside areas by altering

fishing effort (Botsford *et al.* 2003). Since the design of marine reserves is based

upon a great deal of uncertainty, collecting data that are lacking is vital to the

future of the use of MPAs as a fisheries management tool. Using a North

Carolina case study, I have filled in some of these knowledge gaps.

CASE STUDY

In NC, the hard clam (*Mercenaria mercenaria*) fishery had peak landings of

1,393,294 pounds in 1985, which drastically declined to 676,048 pounds in 2000.

In 1989, the commercial value of the fishery peaked at $8,388,051. By 2000, this

amount had dropped to $4,681,053. The sharp declines in landings and value

correspond with a recent study. Peterson (2002) provided evidence that

overharvesting of the hard clam in NC has led to a severe reduction in spawning

stock biomass which in turn resulted in declining recruitment. However, as the

sixth most valuable commercial fishery in NC in 2000, the hard clam remains

crucial to the state. The fishery provides income to fishermen when other

species such as flounder and shrimp are scarce. Therefore it is essential to

determine if the establishment of MPAs restores and protects wild clam populations in traditional harvesting grounds.

Declining catches of *M. mercenaria* by clam fishermen or "clam kickers" in Core Sound, Carteret County, NC, caused the North Carolina Division of Marine Fisheries (NCDMF) to implement a new management strategy in the area (NCDMF Hard Clam Fishery Management Plan, October 2000). Beginning in the fall 2001 season, a mechanical clam harvesting area rotation plan was established for a two- year time period, after which the original clamming grounds would be restored. Approximately 4500 acres of an overharvested area in northern Core Sound was closed and a previously unharvested area of similar size in southeastern Pamlico Sound was opened for two mechanical clam harvesting ("clam kicking") seasons. Then the fishery would revert back to its original areas. Clam kicking is a clam harvesting technique in which a 17- to 45-foot boat is specially outfitted so that the propeller backwash "kicks" or blows the clams from the estuarine bottom into a trawl (Guthrie *et al.* 1982). The implementation of this rotation plan presented me with an optimal natural experiment.

The overall goal of this study is to evaluate whether or not the rotation plan is successful in the protection and perhaps the restoration of clam populations in Core and Pamlico Sounds. My study regarding the mechanical clam harvesting rotation plan in central North Carolina provides unique contributions to the science behind the usage of MPAs as a fishery management tool in several ways. I have collected fishery-independent data:

- that can be used to evaluate the effectiveness of rotating MPAs in managing a fishery by restoring clam populations in an overharvested, traditionally productive area.

- both before and after the implementation of the MPA.

- at multiple points in time.

- inside and outside of the MPA.

- on an MPA created in a soft-bottom habitat.

GOALS OF THE ROTATION PLAN

My hypothesis for the rotation plan consists of 4 goals:

1. To increase clam abundance in the protected area and possibly the opened area of Core Sound

2. To maintain or, at most, slightly decrease clam abundance in Pamlico Sound.

3. To increase overall productivity of the fishery, measured in clam abundance of Core and Pamlico Sound combined

4. To increase recruitment in both sounds by protecting adult spawner populations in Core Sound, measured in sublegal clam abundance of Core and Pamlico Sound

METHODS

Experimental Design

I plan to assess the changes in abundance that occurred in the harvestable clam populations of Core and Pamlico Sounds after implementation of the rotation plan by analyzing my fishery-independent dataset.

The four treatment areas of the study are mapped in Figure 1.1:

   1. **Core-Opened-Closed (COC),** the area in Core Sound that was closed in fall 2001 for two years.

   2. **Core-Opened (CO),** the area in Core Sound that remained opened.

   3. **Pamlico-Closed-Opened (PCO),** the bottom newly opened in fall 2001 for two years (separated into two portions due to the presence of a large seagrass bed).

   4. **Pamlico-Closed (PC),** the only area in southeastern Pamlico Sound that is permanently closed yet also accessible by both clam kicking boat and gear.

I sampled for clams available to the fishery during six different times to detect changes that occurred over 3 years, 1 year before the rotation plan and 2 years after it was implemented (Figure 1.2). To sample for clams and associated data, I used the clam kicking method practiced by local fishermen (Guthrie *et al.* 1982). Although there are variations, the gear that I used for clam kicking sampling had four components that were dragged directly across the sediment. These included a large metal cage that collects the clams, a net that is held open and flush with the bottom of the seafloor with a heavy metal chain, and two wooden "otter trawl" doors. The net funnels the "kicked" clams into the cage.

Additionally, the propeller is adjusted for kicking by directing the wash into the sediment to dislodge the clams. For the first five sampling periods, I utilized the services and boat of Mr. Dallas Goodwin, who owned a 38-foot shrimp trawler outfitted with clam kicking gear. Unfortunately, his boat was destroyed by Hurricane Isabel in September 2003, so I collected data with another clammer who owned a comparable kicking boat.

I directed the fishery-independent sampling and originally developed a random sampling scheme using ArcView GIS. However, the study areas have many shoals, crabpots and impoundment nets which restricted my sampling, resulting in a haphazard sampling scheme. During the six sampling periods I covered each of the four treatment areas as extensively as possible, resulting in a minimum of twelve trawls per treatment area. I counted the number of legal clams (width equal to or greater than one inch or 25.4 mm) caught in each five-minute trawl. I was able to collect relatively few larger sublegal clams, as the gear is designed to exclude sublegal clams less than approximately 0.75 in or 19 mm in width. I retained a minimum of 200 clams total per treatment area for further laboratory analyses including size and age data for spring 2001 and size data for the remaining 5 sampling dates. I noted the type of bycatch and the presence or absence of seagrass (*Zostera marina* in the spring, *Halodule wrightii* in the fall) and oyster cultch. I recorded initial and final water depths using the boat's depth finder, initial and final latitude and longitude by handheld GPS, salinity with a portable refractometer, surface water temperature using a thermometer, and time of day. I attempted to collect data on clam recruits (clams

a few mm in length and a few months in age) in fall 2001 and fall 2002 by using suction dredge apparatus, but overall I found very few recruits so these data are not included in this study.

Using trip ticket data from 1999 to 2005, which are fishery-dependent data collected by NCDMF, I graphed the total number of trips made each season to each sound and the total number of clams caught per season to establish what the fishing effort was before, during and after implementation of the rotation plan.

ANALYSIS AND RESULTS

This section is divided into the 4 goals that I developed for the rotation plan.

Goal 1. Increase legal clam abundance in Core Sound

Figure 1.3 depicts the raw numbers and means of legal clams obtained in individual trawl samples in COC and CO for all six sampling periods. Table 1.1 contains the means and variances of those samples. There appears to be a seasonality effect, as numbers decreased each spring and increased each fall. Overall, the mean numbers of clams caught per trawl increased. In COC, the mean number of clams per trawl in fall 2003 is approximately 7 times the mean in spring 2001, and taking into account the seasonality pattern, the mean in spring 2003 is 3 times the mean in spring 2001 and the mean in fall 2003 is 4 times the mean in fall 2001. In CO, the mean in fall 2003 is 3 times the mean in spring 2001 and 1.5 times the mean in fall 2001. Except for CO in fall, seasonal (spring and fall) pre-rotation legal clam (width => 25.4 mm) counts were significantly

15

different from post-rotation clam counts, because the p values in ANOVAs conducted on the counts were <0.01 (Table 1.2).

The numbers in COC and CO were the same before the rotation plan is implemented. Afterwards, the mean trajectories of COC and CO diverged, with larger numbers occurring in COC, and by the end of the study, about 2.5 times the mean number of clams were caught in COC versus CO. When both COC and CO were opened, there was no evidence for a difference between the areas in the mean number of clams caught per trawl. After COC was closed, there was a systematic change, and by the last sampling time, there was a significant mean difference between COC and CO.

In Appendix 1, two models were developed in order to describe the data-generating mechanism for this dataset. Variance increased directly with mean numbers. This positive relationship between the mean and the variance is typical for count data and was addressed by the models. The first model, the original negative binomial regression model, is depicted in Figure 1.4. The Pearson goodness-of-fit test demonstrates that the lack-of-fit for 5 or 6 cell counts was not significant. Therefore, the negative binomial regression models fit the data. The AIC_c results demonstrated that the mean of the distribution of clams caught per sampling period diverged in COC and CO. In order to determine the direction of the difference, the mean ratio with a 95% confidence interval is calculated, defined as the mean of COC divided by the mean of CO. There were approximately 2.7 times the number of clams caught in COC than CO, and this

16

could have ranged from 1.8 to 4.1 (Table 1.3). There was a significant value by fall 2003 (the mean ratio was significantly greater than one).

The second model, the parsimonious negative binomial regression with seasonality model, takes into account the seasonal pattern to the clam samples, because both COC and CO yielded higher clam numbers in fall than spring (Figure 1.5). For the goodness-of-fit test, the Pearson chi-square was applied and the fit was remarkable. The AIC_c value was smaller (better) than that of the main model. All effects are highly significant (date, season, date/treatment). Of particular importance is that the rate of increase in the clam numbers over time was predicted to be significantly greater in COC than in CO.

Table 1.4 shows that all the 95% confidence intervals (except the first one, by construction) for the parsimonious model do not include one, so they indicate a significant difference. By fall 2003, this model estimated that there were twice as many clams caught per trawl in COC than in CO, and the confidence interval suggests that this value could have ranged from 1.6 to 2.8. The benefits of the new model are that it is more parsimonious (it has less parameters), the AIC_c value is lower (better) than that of the other one, it has remarkable fit (it does not have a lack-of-fit for any group size), and yet it has conclusions similar to those of the original model.

Goal 2. Maintain legal clam abundance in Pamlico Sound

Figure 1.6 depicts the number of legal-sized clams obtained in individual trawl samples in PCO and PC for all six sampling periods. Table 1.5 contains the

means and variances of the clam numbers in PCO and PC for all six sampling periods. The numbers in Pamlico varied more during the course of the study than in Core Sound. In PCO, by the end of the study, the numbers were on average 75% of the original numbers. Considering the seasonality pattern, in spring 2003 the numbers were 30% less than in spring 2001 and 25% more in fall 2003 than in fall 2001. In PC, by the end of the study, the numbers were on average 20% of the original numbers. Taking into account seasonality, the numbers in spring 2003 were 60% of the numbers in spring 2001, and in fall 2003, 65% of those in fall 2001. In both treatments, only spring pre-rotation legal clam (width => 25.4 mm) counts were significantly different from post-rotation clam counts, because the p values in ANOVAs conducted on the counts were <0.05 (Table 1.6). The p values for the ANOVAs performed upon the fall counts were not significant.

Before the plan, PCO and PC were fairly different, but both could produce large numbers. After the implementation of the plan, the mean trajectories initially diverged, but then converged at the last sampling period. Also, after the plan started, large numbers were found only in PC.

Figure 1.7 depicts the negative binomial model applied to the Pamlico Sound dataset. This model type was used because it works well with the Core Sound model described in Appendix 1. The results of Pearson chi-square goodness-of-fit test determined that none of the groupings have a significant lack-of-fit. This model provides strong evidence that the mean number of legal clams per trawl in PCO and PC immediately diverged but then this difference

18

became less important over time. The 95% confidence interval for the mean ratio of PCO to PC was used to determine the direction of the difference (Table 1.7). The results were dramatic: after PCO was opened, the mean number plummeted relative to the number in PC. In spring and fall 2002, the number in PC was 2 to 10 times larger than that in PC. In spring 2003 the number in PC was 1.2 to 10 times larger than in PC (but the mean ratio was still different from one). However, by fall 2003, the mean number of clams was larger in PCO than PC (but not significantly larger).

Goal 3. Increase overall productivity of fishery

In this study, productivity was represented by the mean number of legal clams caught per trawl over the time period of the study. In view of the seasonality pattern, numbers in fall 2003 were 4 times as large as those in fall 2001 in the closed treatments or rotating MPAs (Figure 1.8). In the opened treatments, numbers in fall 2003 were 20% larger than those in fall 2001 (Figure 1.9). In all 4 treatments combined, representing overall productivity of the study area, numbers in fall 2003 were approximately 40% larger than those in fall 2001 (Figure 1.10). Seasonal (spring and fall) pre-rotation legal clam (width => 25.4 mm) counts were both significantly different from post-rotation clam counts, because the p values in ANOVAs conducted on the counts were both <0.05 (Table 1.8). I compared my results with the productivity of the NC commercial hard clam fishery from 2001 to 2003 (Figure 1.11). In the study area, productivity increased by 70%, whereas in the state fishery, productivity declined by 30%. The commercial data include aquaculture catches, so the decline in catches from

wild stock may be greater than 30% if aquaculture production increased during this time period.

Goal 4. Increase sublegal clam abundance in Core and Pamlico Sounds

The clam kicking gear is designed to exclude sublegal clams less than approximately 19 mm in width. I caught very few sublegals (19mm to 25.3 mm in width) overall, but more in Core Sound than in Pamlico. Figure 1.12 depicts the distribution of sublegal clam numbers in Core Sound over the course of the study. The trajectories of the numbers in COC and CO tracked each other, as the means were close or overlapping for all six sampling periods. The trajectories did not follow the paths of the legal clam numbers in COC and CO and did not exhibit the seasonality pattern. P values in ANOVAs conducted on the seasonal (spring and fall) pre-rotation sublegal clam (width < 25.4 mm) counts compared to post-rotation clam counts were not significant except for spring in COC, which was significant at the 0.01 level (Table 1.9) because numbers increased after the rotation plan began but then dropped down to original levels by the end of the study.

In PCO and PC, the mean numbers were close or overlapping for the first five sampling periods (Figure 1.13). PCO had a higher mean in the last sampling period, but this difference was driven by two outliers in PCO (although it is interesting to note that 6 of the 12 numbers of PCO in fall 2003 fall above the highest number for PC). The trajectories did not follow the paths of the legal clam numbers in PCO and PC. Seasonal (spring and fall) pre-rotation sublegal

20

clam (width <25.4 mm) counts were not significantly different from post-rotation clam counts in either treatment (Table 1.10).

In the year prior to the rotation plan (2000 to 2001), there were 892 kicking trips to COC and CO (Figure 1.14). The total number of kicking trips to CO and PCO decreased during the 2 years of the rotation plan to 762 (2001 to 2002) and 741 trips (2002 to 2003), and then the number of trips increased to 1055 (2003 to 2004) after the original areas (COC and CO) were restored. The number of trips to CO during the two years of the rotation plan was 562 and 693, respectively. The number of trips to PCO during the two years of the rotation plan was 200 and 48, respectively.

In the year prior to the rotation plan (2000 to 2001), the total number of clams caught in COC and CO was 1,631,126 (Figure 1.15). The total numbers from CO and PCO during the 2 years of the rotation plan were 1,985,810 (2001 to 2002) and 1,464,559 (2002 to 2003), and then the catch increased to 2,858,534 (2003 to 2004) after the original areas (COC and CO) were restored. The numbers from CO during the two years of the rotation plan were 1,230,462 and 1,294,937, respectively. The numbers from PCO during the two years of the rotation plan were 755,348 and 169,622, respectively.

DISCUSSION

Because of declining commercial hard clam catches, the clam kicking rotation plan was implemented by NCDMF to restore clam populations in the traditionally productive areas. To assess if the rotation plan was successful, I divided my study into 4 goals. The first goal was to increase clam abundance in the protected area of Core Sound (COC) and perhaps the opened area (CO). According to the results of my study, both elements of the first goal were met. In COC, abundance of legal clams significantly increased over time. Incorporating the seasonality pattern, numbers in the spring increased by 3-fold and numbers in the fall increased by 4-fold. In CO, abundance of legal clams significantly increased 2-fold in spring. Although not significantly different, the mean in fall 2003 was 1.5 times the mean in fall 2001. COC and CO produced the same mean numbers in the beginning, but by the end COC had 2.5 times the catches of CO. Two models were fit to the data, and both of them indicated that by the end of the study, there was a significant increase in clam populations in COC relative to CO (numbers in COC ranging from 1.6 to 4 times the numbers in CO).

Halpern and Warner (2002) reviewed the efficacy of marine reserves and found an average increase of 91% in population densities within reserve boundaries, often in short time periods of one to three years. The results of this study indicate that rotating MPAs in this fishery is more successful than the average marine reserve, because increases in clam abundance ranged from 1.5 to 4 times the original amount in a two-year time period.

The second goal was to accomplish the first while maintaining or slightly decreasing clam abundances in Pamlico Sound (PCO or PC). It is not clear if this second goal was met, because the numbers in Pamlico Sound varied considerably more than those in Core Sound. In PCO, the mean numbers at the end of the study were 75% of the original mean numbers. Considering the seasonality pattern, in spring 2003 the numbers were 70% less than in spring 2001 (significantly different) and 25% more in fall 2003 than in fall 2001. In PC the mean numbers at the end of the study were only 20% of the original mean numbers. Taking into account seasonality, the numbers in spring 2003 were 60% of the numbers in spring 2001 (significantly different), and in fall 2003, 65% of the numbers in fall 2001. Therefore, if I only take into account significant results (the spring data) clam abundance decreased during the study in both areas. However, in PCO, there was a non-significant increase in fall numbers (and a non-significant decrease in PC in fall numbers). Also, after the plan started, large numbers were found only in PC. Future analyses or studies involving predation or habitat destruction (particularly of seagrass) may help to explain the variable results that I found in Pamlico Sound.

 A negative binomial regression model was fit to the Pamlico Sound dataset (similar to the original Core Sound model). In PCO, there was an immediate decrease in the mean numbers of legal clams, for within the first year of the rotation plan the clam population in PC was approximately 2 to 10 times larger than the one in PCO. By the end of the study, these differences no longer existed.

At this point it was necessary to address the seasonality pattern exhibited by Core Sound, in which numbers were larger in fall than in spring. Both COC and CO have been extensively fished. The kicking season occurred just prior to spring sampling, decreasing adult abundances. Smaller clams then had summer and fall to grow to legal size, resulting in increased catches in the late fall. Before the plan, PCO and PC behaved erratically, but these were the natural dynamics of the populations since they had not been exposed to fishing. After the plan was implemented, PCO was subject to systematic harvesting each season, and in spring and fall 2002 it began to exhibit the Core Sound pattern of seasonality. PC continued to behave normally, with its own erratic dynamic. These results suggest that fishing converted COC and CO to this common pattern of seasonality with an artificial oscillation in the past, and then converted PCO to that pattern.

The third goal is to increase overall productivity of the fishery, measured in clam abundance of Core and Pamlico Sound combined. The results of this study indicate that this goal is met. Combined numbers for all 4 treatments, representing overall productivity of the study area, were approximately 40% larger in fall 2003 than in fall 2001, and this difference was significant. These results are more striking when placed in a broader context. Based upon annual averages for 2001, 2002 and 2003, productivity in the study area increased by 70%, compared to productivity of the entire state fishery, which declined by 30%. The decline in catches from wild stock may be greater than 30%, because these data include aquaculture production which may have increased during this time

period. Therefore, the trade-off of opening a previously protected area (PCO) with closing a previously productive but overharvested area (COC) was successful in not only increasing clam abundances in COC but also in increasing the overall productivity of the fishery.

The fourth goal was to protect adult spawner populations in COC, eventually resulting in increased sublegal clam abundance in Core and Pamlico Sounds. Relatively few sublegal clams were caught during the study, so this goal was difficult to assess. However, more were caught in Core Sound than in Pamlico Sound. The only significant difference in sublegal clam numbers occurred in the spring samples from COC. The catches increased after the first season of the rotation plan, but then decreased after the second season to original levels.

Due to fishing gear restrictions, I was unable to catch most of the sublegals that recruited to the clam populations after implementation of the rotation plan. Since I rarely found clam recruits during my suction dredge sampling in fall 2001 and 2002, I was unable to collect a useful sample of clams that had recently recruited to the clamming areas (larvae released in June-July and settled soon afterwards). This is not unusual: Kraeuter and Castagna (2001) state that new *M. mercenaria* recruits are usually difficult to find but when the clams are older, that particular age class is present. However, I may have been unable to catch the recruits because, in central NC, overfishing of clam populations has led to severe reductions in recruitment (Peterson 2002). Future

analyses or studies of the age-size structure of the clam populations may help determine if the fourth goal is met.

The pattern of increased clam abundance in my sampling that suggests higher productivity after the rotation plan was implemented can not be explained by a large reduction in fishing effort that allowed more clams to survive the fishing. The trip ticket data showed that the total number of trips across the opened areas actually increased from before to after the rotation.

This study contributes to the body of knowledge of MPAs. In his review on the efficacy of marine reserves, Halpern (2003) found that only a few studies sampled more than one time, had before and after data, collected data inside and outside the boundaries, and studied soft-bottom habitats; this study fulfilled all of these shortcomings. Although it would be ideal biologically to establish a fully protected marine reserve, rotating MPAs that are temporally and/or spatially rotated are more practical than permanent marine reserves because of their greater acceptance by user groups. Among the user groups in NC, the rotation plan was extremely controversial. A total closure of Core Sound for any time period or a permanent closure of any clamming ground would not have been acceptable. The rotation plan is a compromise that is successful for the hard clam fishery in NC, as this study provides strong evidence that rotating MPAs restored clam populations in both opened and closed areas that were traditionally productive but recently overfished. During the study period, the overall productivity of the study area increased by 70%, which is more remarkable when compared to the 30% decline in the statewide NC commercial fishery.

Chapter 1 Figures.
The effects of rotating Marine Protected Areas (MPAs) on the productivity of the North Carolina hard clam (*Mercenaria mercenaria*) fishery.

Figure 1.1. Map of the study area in Carteret County, NC, with marked treatment areas.

Mechanical Clam Harvesting Rotation Plan: Treatment Areas

Pamlico Sound

Study Site

Core Sound

PCO

PCO

PC

COC

CO

PCO = Pamlico-Closed-Opened (2 areas in Pamlico Sound newly opened in Fall 2001)
PC = Pamlico-Closed (area in Pamlico Sound permanently closed)
COC = Core-Opened-Closed (area in Core Sound closed in Fall 2001 due to overharvesting)
CO = Core-Opened (area in Core Sound permanently opened)
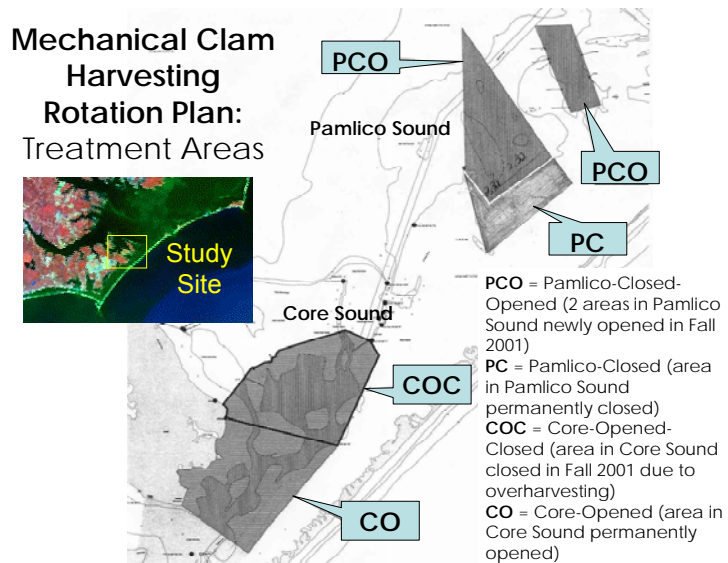
Figure 1.2. Timeline of sampling for the study.

Figure 1.3. Distribution of legal clam catches at each sampling period for COC and CO. The coordinates of the samples were randomly jittered to prevent overlap. Before the rotation plan, there were very similar catches in COC and CO. Afterwards, the mean trajectories of COC and CO diverged, with larger catches found in COC. However, there was a positive relationship between the mean and variance, as the variance increased directly with mean catch. This was further evidence for a model that is not normal-based. There appeared to be a seasonality effect, as catches decreased each spring and increased each fall.
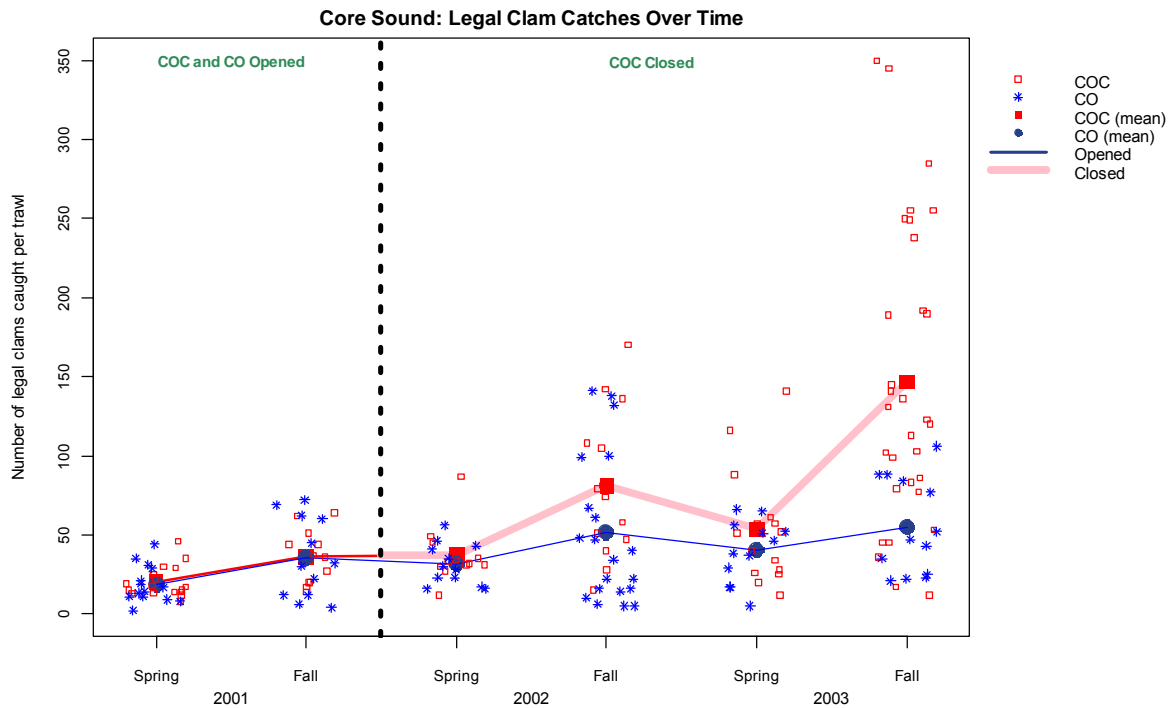
Table 1.1. Mean numbers of clams per five-minute trawl with variances for all six sampling periods in COC and CO in Core Sound.

Sampling Period		Core Sound			
		CO		COC	
		Mean	Variance	Mean	Variance
2001	Spring	18.86	140.90	20.29	96.97
	Fall	35.50	639.91	36.33	295.52
2002	Spring	31.17	172.15	37.17	327.97
	Fall	51.15	2166.56	81.00	2112.00
2003	Spring	39.92	388.63	53.69	1231.56
	Fall	54.69	907.40	146.58	8709.52

Table 1.2. For Core Sound (CO and COC), a one-way ANOVA is used to test whether seasonal (spring and fall) pre-rotation legal clam (width >= 25.4 mm) counts are different from post-rotation clam counts. This type of count data conforms to the negative binomial distribution and there are some zero counts, so the data were transformed prior to analysis using ln (count+1) to meet the normality assumption of ANOVA. Levene's test for homogeneity of variance was examined and Welch's corrected F and p value were used when necessary (indicated by "Welch's" below the p value.) ANOVA notation used: df, degrees of freedom; MSE, mean square error; F, F ratio; p value, probability.

		CO: Legals					COC: Legals			
Source of Variation		df	MSE	F	p value		df	MSE	F	p value
Spring	Year	1	3.97	10.32	<0.01		1	5.70	21.57	<0.01
	Error	36	0.38		*0.22*		43	0.26		*0.33*
	Total	37			*R-Square*		44			*R-Square*
Fall	Year	1	1.16	1.4	0.2425		1	10.87	19.80	<0.01
	Error	43	0.83		*0.03*		55	0.55		*0.26*
	Total	44			*R-Square*		56			*R-Square*

Figure 1.4. Predicted mean legal clam catches at each sampling period for COC and CO compared to observed mean catches, based on the original negative binomial regression model. Jittered raw data were superimposed.

Core Sound: Results for Original Negative Binomial Regression Model
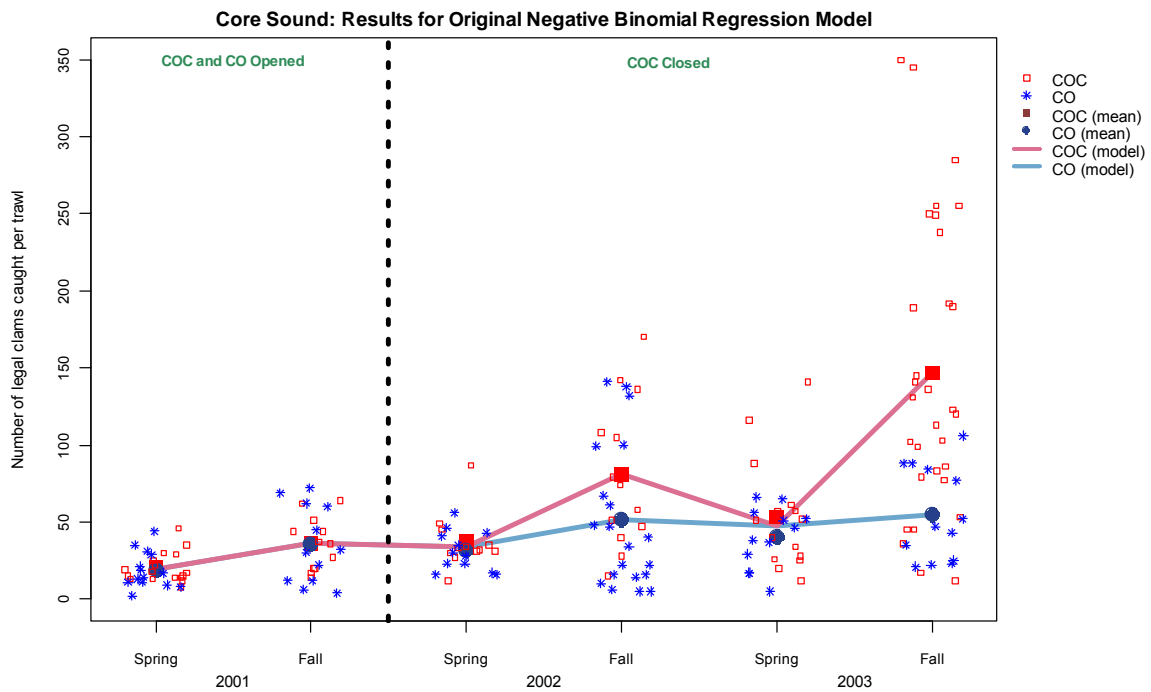
Table 1.3. 95% confidence intervals for the mean ratio of the Core Sound samples. The asterisk denoted the sampling period in which the mean ratio reached statistical significance (ratio was significantly greater than 1, α=.05).

Date		Mean Ratio (COC/CO)	95% C. I. for the Mean Ratio
2001	Spring	1.08	(0.74, 1.56)
	Fall	1.02	(0.61, 1.72)
2002	Spring	1.19	(0.86, 1.66)
	Fall	1.58	(0.91, 2.74)
2003	Spring	1.34	(0.87, 2.09)
	Fall	2.68	*(1.76, 4.09)

Figure 1.5. Predicted mean clam catches at each sampling period for COC and CO compared to observed mean catches, based on the parsimonious negative binomial regression with seasonality model. Jittered raw data were superimposed.

Core Sound: Results for Parsimonious Negative Binomial Regression w/Seasonality Model
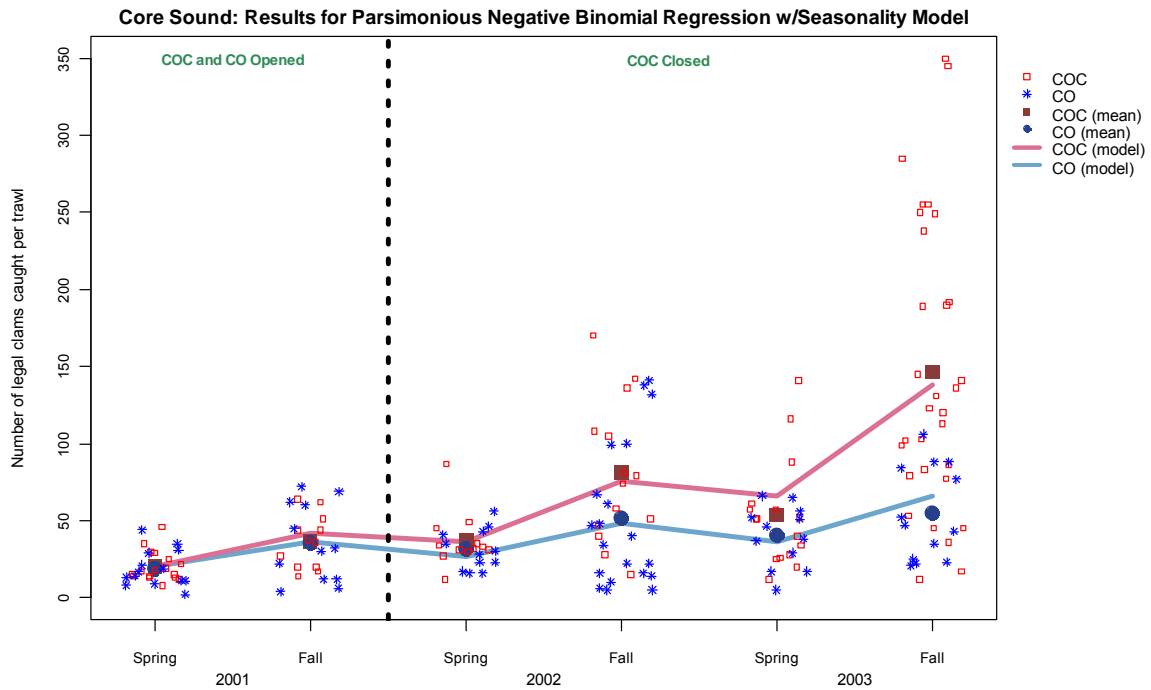
Table 1.4. 95% confidence intervals for the mean ratio of the Core Sound samples for the parsimonious model. Note that all confidence intervals were significant (except the first one, by construction). The asterisk denotes the sampling periods for which the confidence intervals were significant (ratio was significantly greater than 1, α=.05).

Date		Mean Ratio (COC/CO)	95% C. I. for the Mean Ratio
2001	Spring	1.00	(1.00, 1.00)
	Fall	1.16	*(1.09, 1.23)
2002	Spring	1.34	*(1.20, 1.51)
	Fall	1.56	*(1.31, 1.86)
2003	Spring	1.81	*(1.43, 2.28)
	Fall	2.10	*(1.57, 2.80)

Figure 1.6. Distribution of legal clam catches at each sampling period for PCO and PC. The coordinates of the samples were randomly jittered to prevent overlap. In PCO, after implementation of the rotation plan, there was an immediate decrease in the mean numbers of legal clams. PC had higher mean catches until the last sampling period, when there was no longer a difference between the two areas.
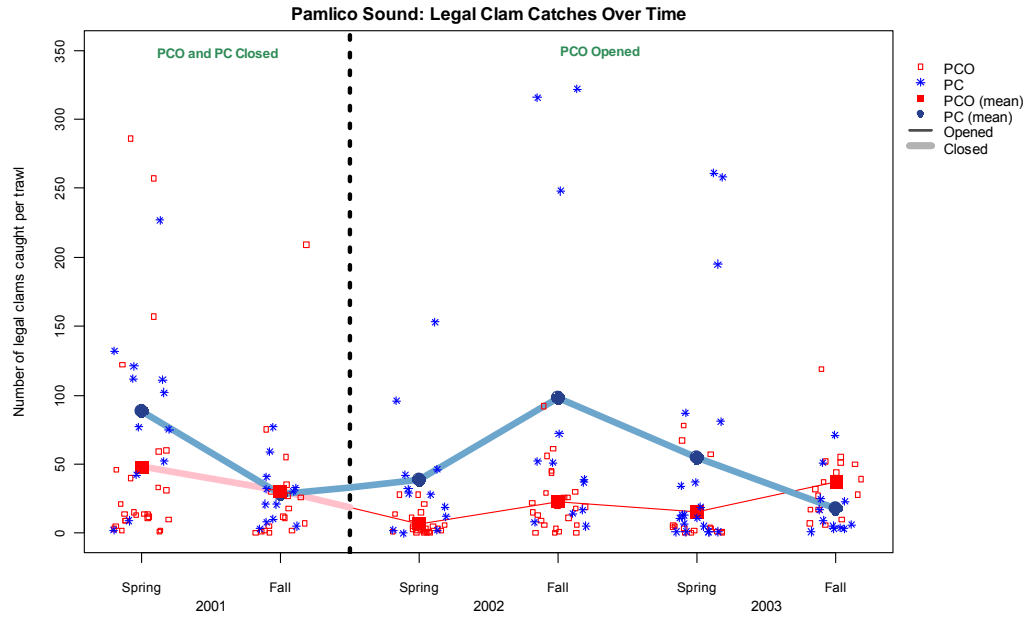
Table 1.5. Mean numbers of clams per five-minute trawl with variances for all six sampling periods in PCO and PC in Pamlico Sound.

Sampling Period		Pamlico Sound			
		PC		PCO	
		Mean	Variance	Mean	Variance
2001	Spring	88.50	3725.73	47.92	5700.23
	Fall	28.33	504.61	30.29	2558.22
2002	Spring	38.42	1996.08	6.87	74.66
	Fall	98.42	14796.99	23.04	496.96
2003	Spring	54.58	7432.59	15.40	741.54
	Fall	18.17	481.97	36.94	752.46

Table 1.6. For Pamlico Sound (PC and PCO), a one-way ANOVA is used to test whether seasonal (spring and fall) pre-rotation legal clam (width >= 25.4 mm) counts are different from post-rotation clam counts. This type of count data conforms to the negative binomial distribution and there are some zero counts, so the data were transformed prior to analysis using ln (count+1) to meet the normality assumption of ANOVA. Levene's test for homogeneity of variance was examined and Welch's corrected F and p value were used when necessary (indicated by "Welch's" below the p value.) ANOVA notation used: df, degrees of freedom; MSE, mean square error; F, F ratio; p value, probability.

		PC: Legals				PCO: Legals			
Source of Variation		df	MSE	F	p value	df	MSE	F	p value
Spring	Year	1	13.23	5.8	0.02	1	32.43	20.03	<0.01
	Error	41	2.28		*0.12*	62	1.62		*0.24*
	Total	42			*R-Square*	63			*R-Square*
Fall	Year	1	0.04	0.02	0.88	1	2.30	1.38	0.25
	Error	34	1.63		*0.00*	56	1.67		*0.023*
	Total	35			*R-Square*	57			*R-Square*

Table 1.7. 95% confidence intervals for the mean ratio of the Pamlico Sound samples for the best negative binomial regression model fit at each sampling period. The asterisk denotes the sampling periods in which the mean ratio was statistically significant (ratio was significantly different from 1, α=.05).

Date		Mean Ratio (PCO/PC)	95% C. I. for the Mean Ratio
2001	Spring	0.54	(0.25, 1.19)
	Fall	1.07	(0.44, 2.61)
2002	Spring	0.18	*(0.07, 0.43)
	Fall	0.23	*(0.11, 0.51)
2003	Spring	0.28	*(0.10, 0.83)
	Fall	2.03	(1.05, 3.93)

Figure 1.7. Predicted mean clam catches at each sampling period for PCO and PC compared to observed mean catches, based on the negative binomial regression model that was the best fit at each sampling period (similar to the original Core Sound model). Jittered raw data were superimposed. In PCO, there was an immediate decrease in the mean numbers of legal clams, for within the first year of the rotation plan, the clam population in PC was approximately 2 to 10 times larger than the one in PCO. By the end of the study, these differences no longer existed.
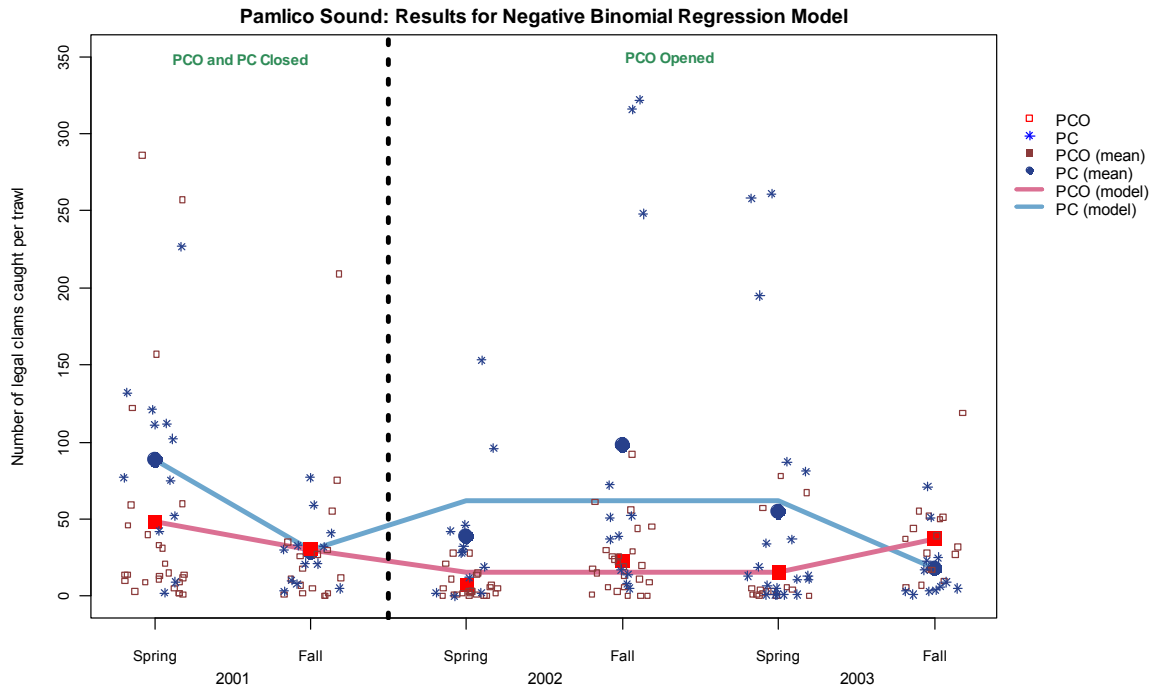
Figure 1.8. Productivity of the closed treatments (rotating MPAs) during the study period, graphed as mean number of legal clams caught per trawl over time.

Closed Treatments: Legal Clam Catches Over Time

	SPR 2001	FALL 2001	SPR 2002	FALL 2002	SPR 2003	FALL 2003
Mean	60.7	29.5	37.8	89.0	54.2	110.7
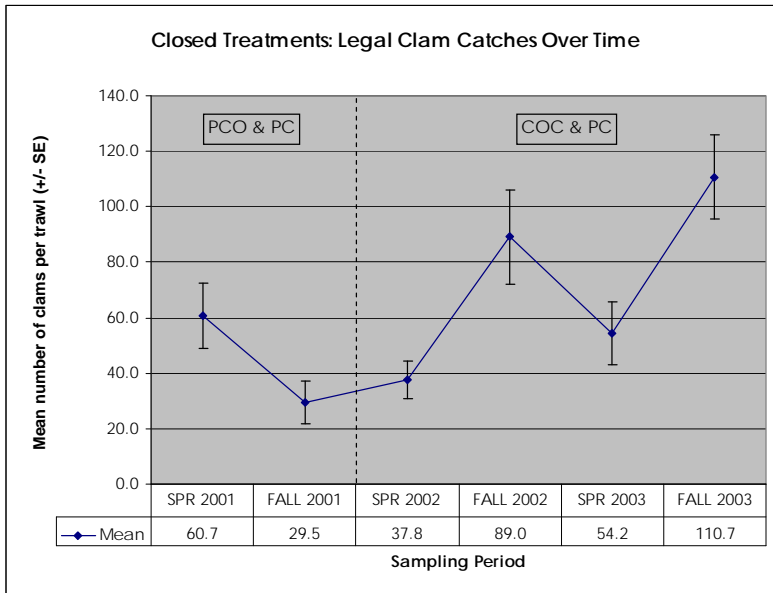
Figure 1.9. Productivity of the opened treatments during the study period, graphed as mean number of legal clams caught per trawl over time.

Opened Treatments:
Legal Clam Catches Over Time

Mean	SPR 2001	FALL 2001	SPR 2002	FALL 2002	SPR 2003	FALL 2003
Mean	19.6	35.9	15.2	35.5	26.3	44.9
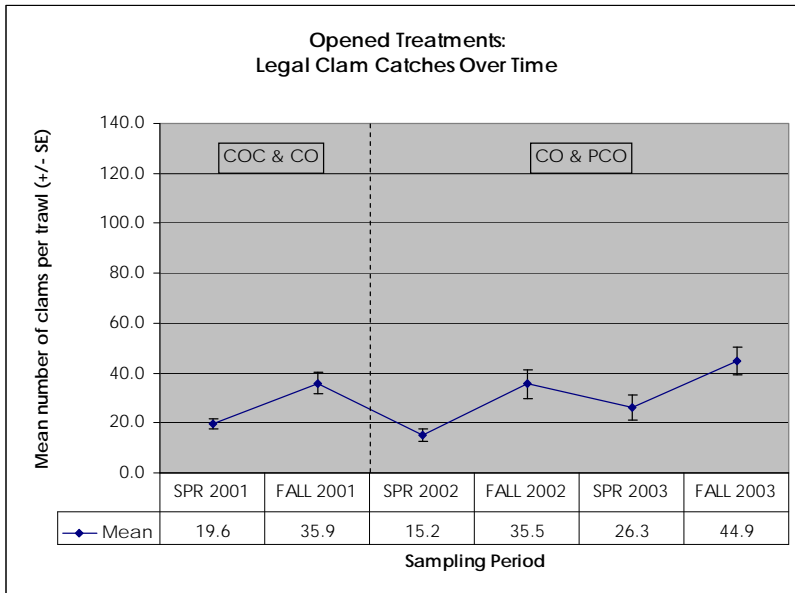
Figure 1.10. Productivity of all 4 treatment areas combined during the study period, graphed as mean number of legal clams caught per trawl over time.

Core and Pamlico Sounds (All 4 Treatments):
Legal Clam Catches Over Time

	SPR 2001	FALL 2001	SPR 2002	FALL 2002	SPR 2003	FALL 2003
Mean	42.3	32.4	24.4	55.1	42.0	84.2

Sampling Period
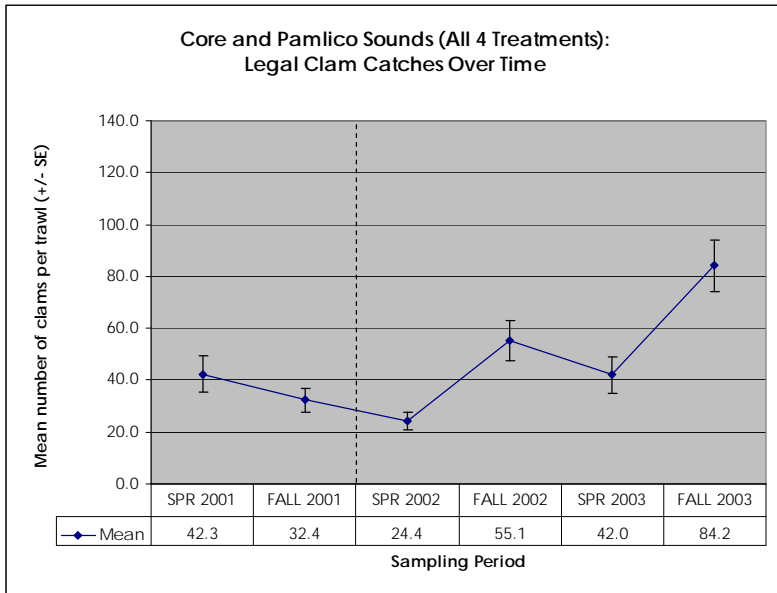
Table 1.8. For all 4 treatments, a one-way ANOVA is used to test whether seasonal (spring and fall) pre-rotation legal clam (width >= 25.4 mm) counts are different from post-rotation clam counts. This type of count data conforms to the negative binomial distribution and there are some zero counts, so the data were transformed prior to analysis using ln (count+1) to meet the normality assumption of ANOVA. Levene's test for homogeneity of variance was examined and Welch's corrected F and p value were used when necessary (indicated by "Welch's" below the p value.) ANOVA notation used: df, degrees of freedom; MSE, mean square error; F, F ratio; p value, probability.

		All 4 Treatments				
Source of Variation		df	MSE	F	p value	
Spring	Year	1	6.33	*4.21*	*0.04*	
	Error	188	1.72	*Welch's*	*0.02*	
	Total	189			*R-Square*	
Fall	Year	1	14.80	9.86	<0.01	
	Error	194	1.50		*0.04*	
	Total	195			*R-Square*	

Figure 1.11. Comparison of the overall productivity of the study area with the commercial NC hard clam fishery during the study period. The commercial data includes aquaculture catches, so the decline of wild stock may be greater than 30%.

**Total Commercial Hard Clam Landings in NC versus
Mean Number of Clams per Trawl in Rotational MPA (All Treatments, Opened and Closed)**

Rotational MPA
70% Increase

NC Commercial Catch
30% Decline

Rotation

Year

Catch in millions of lbs

Mean number of clams per trawl in lbs
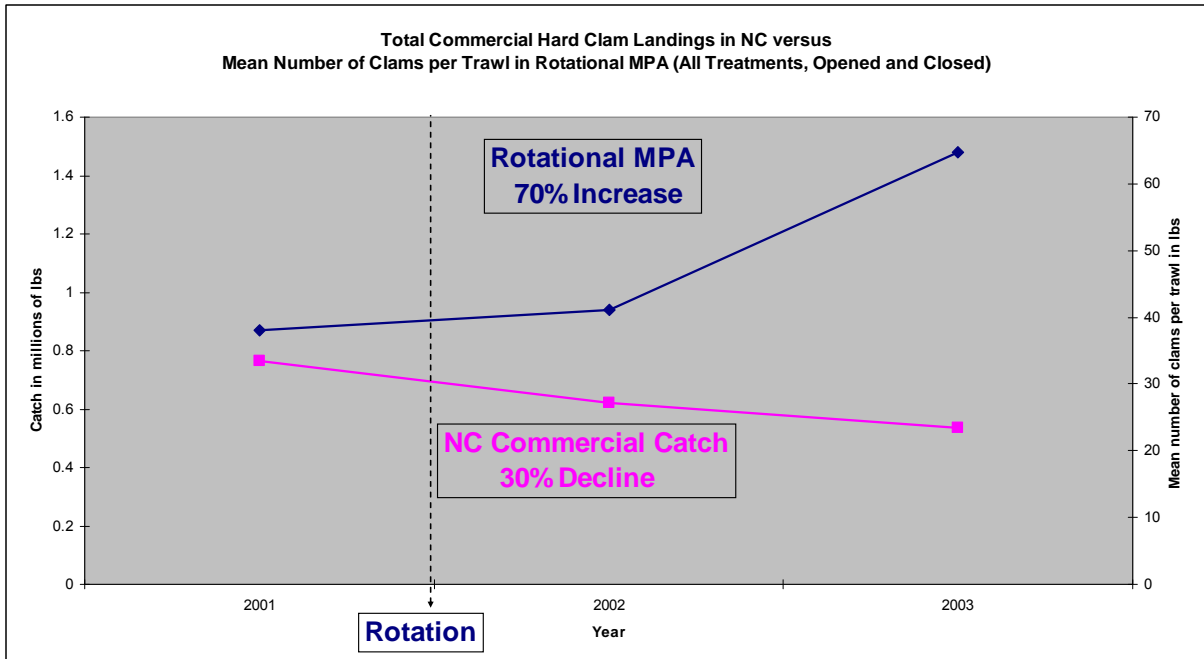
Figure 1.12. Distribution of sublegal clam catches at each sampling period for COC and CO. The coordinates of the samples were randomly jittered to prevent overlap. The means of COC and CO were very similar during all six sampling periods. The trajectories did not match those of legal clams in Core Sound or exhibit the seasonality pattern.
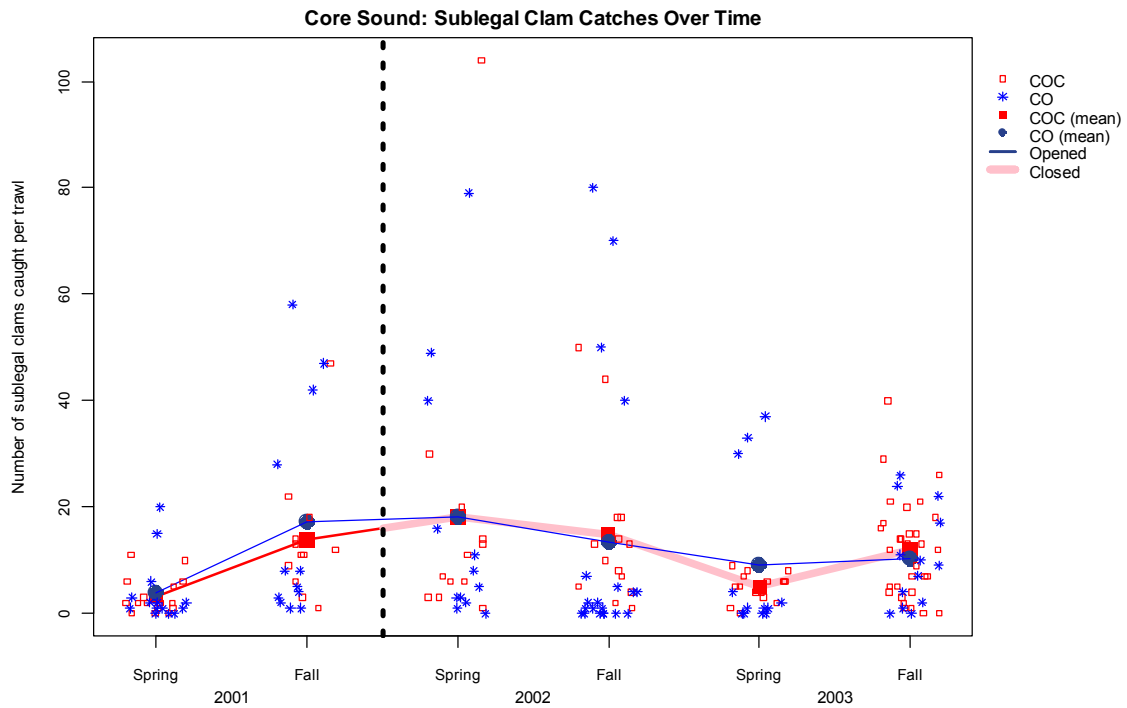
Table 1.9. For Core Sound (CO and COC), a one-way ANOVA is used to test whether seasonal (spring and fall) pre-rotation sublegal clam (approximate width ranging from 19 to 25.3 mm) counts are different from post-rotation clam counts. This type of count data conforms to the negative binomial distribution and there are some zero counts, so the data were transformed prior to analysis using ln (count+1) to meet the normality assumption of ANOVA. Levene's test for homogeneity of variance was examined and Welch's corrected F and p value were used when necessary (indicated by "Welch's" below the p value.) ANOVA notation used: df, degrees of freedom; MSE, mean square error; F, F ratio; p value, probability.

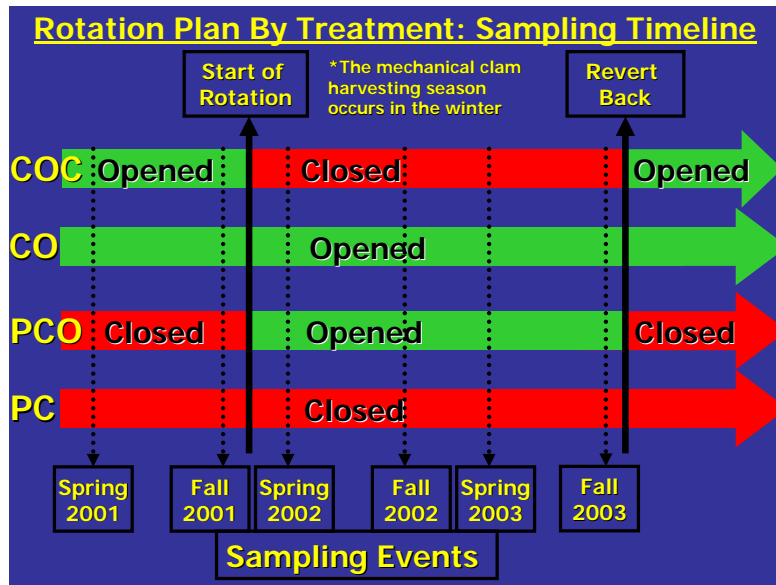|		CO: Sublegals				COC: Sublegals			
Source of Variation		df	MSE	F	p value	df	MSE	F	p value
Spring	Year	1	3.53	2.14	0.15	1	6.60	9.24	<0.01
	Error	36	1.65		*0.06*	43	0.71		*0.18*
	Total	37			*R-Square*	44			*R-Square*
Fall	Year	1	3.45	1.84	0.18	1	0.23	0.27	0.60
	Error	43	1.88		*0.04*	55	0.83		*0.00*
	Total	44			*R-Square*	56			*R-Square*

Figure 1.13. Distribution of sublegal clam catches at each sampling period for PCO and PC. The coordinates of the samples were randomly jittered to prevent overlap. Note that very few sublegal clams were caught. The trajectories of PCO and PC matched each other until the last sampling period, but this difference was caused by two outliers.
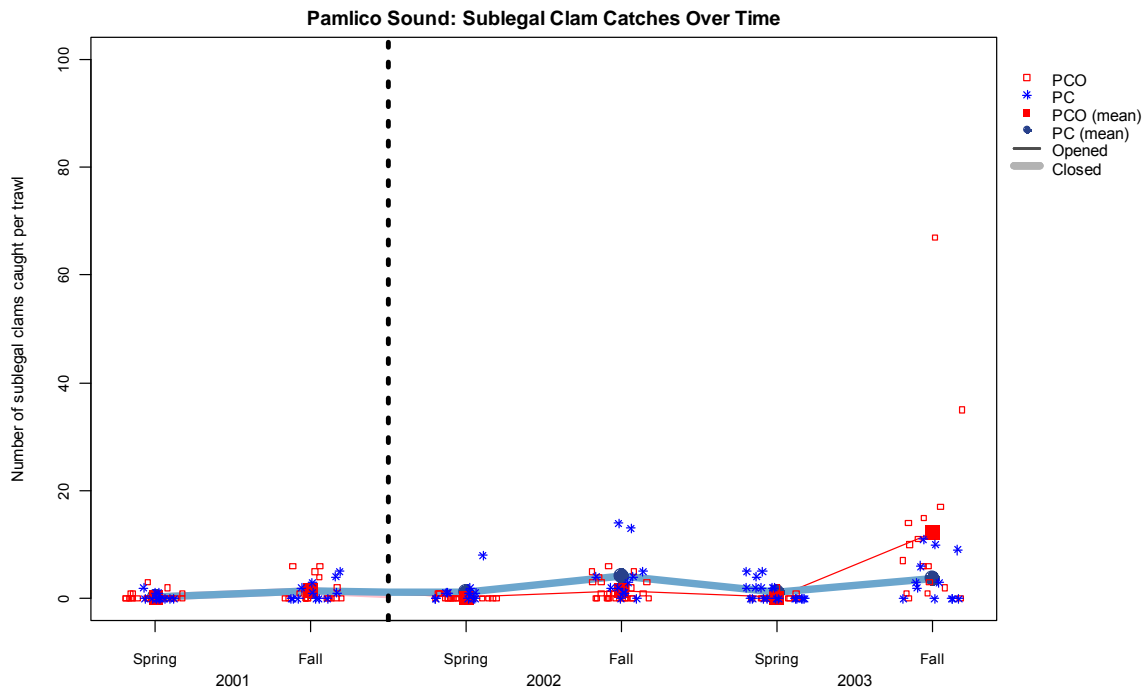
Table 1.10. For Pamlico Sound (PC and PCO), a one-way ANOVA is used to test whether seasonal (spring and fall) pre-rotation sublegal clam (approximate width ranging from 19 to 25.3 mm) counts are different from post-rotation clam counts. This type of count data conforms to the negative binomial distribution and there are some zero counts, so the data were transformed prior to analysis using ln (count+1) to meet the normality assumption of ANOVA. Levene's test for homogeneity of variance was examined and Welch's corrected F and p value were used when necessary (indicated by "Welch's" below the p value.) ANOVA notation used: df, degrees of freedom; MSE, mean square error; F, F ratio; p value, probability.

		PC: Sublegals				PCO: Sublegals			
Source of Variation		**df**	**MSE**	**F**	**p value**	**df**	**MSE**	**F**	**p value**
Spring	**Year**	1	1.09	2.93	0.09	1	0.05	0.43	0.51
	Error	41	0.37		*0.07*	62	0.11		0.00
	Total	42			*R-Square*	63			*R-Square*
Fall	**Year**	1	2.63	3.44	0.07	1	4.17	3.76	0.06
	Error	34	0.77		*0.09*	56	1.10		*0.06*
	Total	35			*R-Square*	57			*R-Square*

Figure 1.14. For Core and Pamlico Sounds, Carteret County, NC, the total number of clam kicking trips made during each kicking season for the years 1999-2005. This graph was based upon data collected by the NCDMF Trip Ticket Program. The locations of the trips were recorded only as Core or Pamlico Sound, therefore in the years before and after the rotation plan, I was unable to determine if trips were made to COC or CO.

Core and Pamlico Sounds:
Number of Clamming Trips per Kicking Season (1999-2005)

	1999 to 2000	2000 to 2001	2001 to 2002	2002 to 2003	2003 to 2004	2004 to 2005
PCO			200	48		
COC & CO	570	892			1055	693
CO			562	693		

Season (Dec.-March)
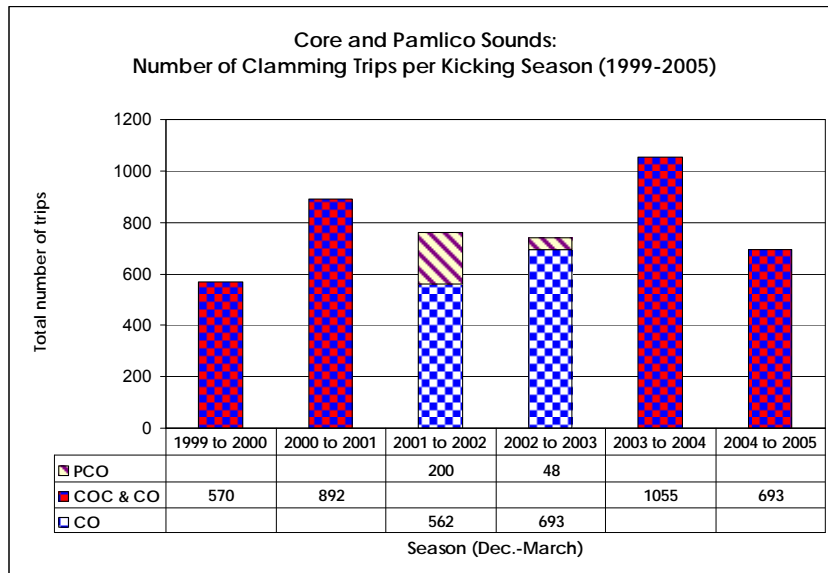
Figure 1.15. For Core and Pamlico Sounds, the total numbers of harvested clams during each kicking season for the years 1999-2005.

Core and Pamlico Sounds:
Numbers of Clams Caught per Kicking Season (1999-2005)

	1999 to 2000	2000 to 2001	2001 to 2002	2002 to 2003	2003 to 2004	2004 to 2005
PCO	-	-	755,348	169,622	-	-
COC & CO	1,364,657	1,631,126	-	-	2,858,534	1,644,904
CO	-	-	1,230,462	1,294,937	-	-

Season (Dec.-March)

51
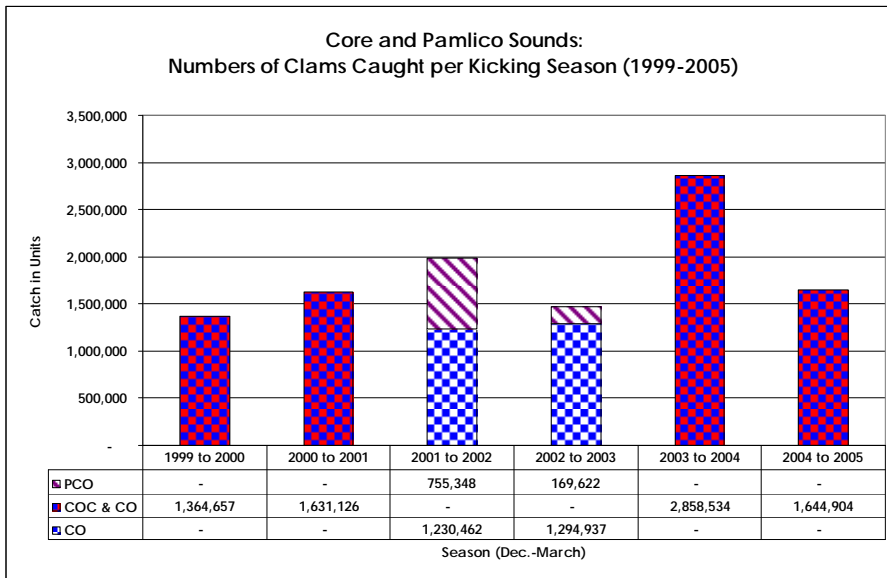
Chapter 1 Appendix.
The effects of rotating Marine Protected Areas (MPAs) on the productivity of the North Carolina hard clam (*Mercenaria mercenaria*) fishery.

Part 1. Legal Clam Populations in Core Sound

Model choices for count or frequency data

The data of interest are the number of legal clams collected per five-minute trawl, which are count or frequency data. Counts are both discrete and bounded by zero, and this influences the choice of statistical model.

There are three model choices for dealing with counts:

1. If counts are all large, standard statistics that assume a normal distribution can be used without manipulating the raw data.

2. If counts are moderately large (~8 or larger), a transformation is needed. For count data, these are usually square root and logarithm transformations. The lognormal probability model is useful in biology, for if log-transformed data are normally distributed, then the original data are lognormally distributed. Zeros are not allowed, so if there are zero counts, a positive constant k must be added to all observations y and log $(y + k)$ is analyzed as the response variable.

3. If there are some small counts, the discrete probability distribution can

be used to analyze the raw data without manipulating them. If the

probability distribution is exponential (such as the Poisson and negative

binomial) a generalized linear model is appropriate.

Figure 1A.1 is a histogram composed of the distribution of legal clam

catches summed for 185 trawl samples taken in both COC and CO during the six

sampling periods. All times and treatments are grouped together as there are

not enough numbers for the individual sampling events to be done individually.

Maximum likelihood estimates of lognormal and negative binomial densities are

superimposed onto the overall distribution and both fit the data reasonably well.

Therefore, normal-based statistical methods do not apply to these data.

Quantifying the mean-variance relationship

The variability of the catches basically increase with the mean of the catches

(Figure 1.3). This differs from a normal distribution, in which the mean and

variance are independent of each other. To apply ANOVA, one would compare

the mean profiles of COC and CO over time. However, one of the assumptions

of ANOVA is homogeneity of variance. Although the means may vary between

treatments and sampling periods, the variances may not. If they do vary, this is

heteroscedasticity. Least squares regression is used to test for homogeneity by

determining which probability model matches the mean-variance relationship

(Table 1A.1). I tested for Poisson, scaled Poisson, negative binomial, lognormal

and gamma models. Negative binomial and lognormal models fit the Core Sound data almost perfectly, with the exception of one control site discussed later (Figure 1A.2). These data are heteroscedastic (so Poisson models are not appropriate). The negative binomial model is a better choice than the lognormal one, because it is a discrete distribution, just like that of the clam catches (note that the ANOVA tables used in the main text of Chapter 1 are calculated for a different set of factors). Since count data can also be log-transformed and then fit to a normal-based model, normal-based models are included as well.

Comparison of Probability Models

Although various statistical models for a particular system must have the same response variable, they can differ in three ways: predictors, link functions (for generalized linear models) and error specifications. The error specification is altered by changing the probability model, which also can be thought of as a data-generating mechanism, for the error distribution is the probabilistic mechanism that may have generated the collected data.

3 Questions Considered for Analysis of Legal Clams in Core Sound

1. Which probability distribution best fits the data-generating mechanism for this dataset?

2. For a specific sampling period, are there differences in the number of legal clams caught in the treatment (COC) versus control (CO) areas?

3. Do these differences change over time?

Question 1. Which probability distribution best fits the data-generating mechanism for this dataset? The four model classes used are in Table 1A.2.

Question 2. For a specific sampling period, are there differences in the number of legal clams caught in COC versus CO? To answer this question, two versions of each of the four model classes in Table 1A.2 are fit (Table 1A.3). Additionally, two additional models are fit only to the negative binomial probability distribution (Table 1A.4). The negative binomial is a two-parameter distribution with the parameters of the mean u and a dispersion parameter k. Often k is treated as a nuisance parameter (a quantity that is adjusted to provide a reasonable fit to the data). In this case, the magnitude of k may indicate how clams are distributed in the environment, so it is important in this analysis. Between Questions 1 and 2, there are 10 models fit.

Question 3. Do these differences change over time? This is tested by fitting all models separately at each of the six sampling periods to determine which models have the best fit over time. This comparison is done by AIC_c values, the second order Akaike information criterion. This is used instead of AIC because the ratio of the sample size to the number of estimated parameters is small. The smaller the AIC_c value, the better the fit. The value has no meaning on its own, only when it is compared to the AIC_c of other models.

Application of the models

Table 1A.5 lists the model with the best (least) AIC_c value for each sampling period. With the exception of spring 2002, the best models are negative binomial regression models. Since the model rankings using the AIC_c values are only slightly different from each other, further analysis using Akaike weights is done. Akaike weights provide the fraction of time under repeated sampling that the model in question would be ranked at the top of the list. In this assessment, the lognormal model that is the best model for spring 2002 is comparable to the negative binomial regression model, so for simplicity the lognormal one is dropped. Table 1A.6 contains the Akaike weights for the negative binomial regression models, which are then plotted in Figure 1A.3. When both COC and CO are opened, there is no evidence for a difference between the areas in the mean number of clams caught per trawl. After COC is closed, there is a systematic change, and by the last sampling time, there is a significant mean difference between COC and CO.

For the negative binomial regression model, I contrast the effects of dispersion and mean parameters on the distribution of clam catches. The dispersion effects appear to be simple random oscillations, although there may be a seasonal component, as the evidence for dispersion differences is greater in the fall than the spring. The common and different dispersion models are not that different, so I continue with the treatment, or common dispersion, different mean model (Figure 1.4).

The AIC_c results demonstrate that the mean of the distribution of clams caught per sampling period diverge in COC and CO, but these results do not

determine the direction of the difference. Since the mean effect only model is used, the mean ratio is determined, which is the mean of COC divided by the mean of CO. The 95% confidence interval for the mean ratio for each sampling period is calculated (Table 1.3). There is a significant value by fall 2003 (the mean ratio is significantly greater than one). The AIC_c results are supported by the confidence intervals. When both COC and CO are opened, their mean ratio is approximately one. Once COC is closed, the mean number of clams per trawl in COC exceed the mean found in CO. By fall 2003, the mean ratio is statistically significant. The confidence intervals suggest that the mean number of legal clams caught in COC is between 1.8 and 4 times greater than the number obtained in CO.

Goodness-of-fit for the Core Sound negative binomial regression model

Since the clam counts are a form of categorical data, standard categorical goodness-of-fit tests are applied. There are two steps involved in applying goodness-of-fit tests. The first one is to create a graph of the fit by plotting the observed and predicted probability distributions. The second is to compare these by the Pearson chi-square test.

The mean number of legal clams does not vary between COC and CO for the majority of the sampling periods. However, the overall mean varies over time and this is incorporated into the model. A categorization plan in which the expected counts that meet the minimum cell count restrictions but still have a sufficient number of degrees of freedom to keep the test meaningful

accomplished this goal. For the minimum cell count, conventional guidelines

suggest that expected counts should be five or greater for assumptions to hold.

If the number of categories is too few, the number of degrees of freedom left to

carry out the test is insufficient. If 7, 8, or 9 cell counts are used, the data is over-

fit (used up most of the degrees of freedom by estimating more parameters than

the number of categories present justifies). At 10 or more there are no more

degrees of freedom for the chi-square distribution. Cell counts of 5 or 6 remain.

This same set of categories is applied to the observed categories. The Pearson

goodness-of-fit test demonstrates that the lack-of-fit for 5 or 6 cell counts is not

significant. Therefore, the negative binomial regression models fit the data and

the conclusions from the model are legitimate (Figure 1A.4).

***Theoretical basis for applying negative binomial regression models to clam
kicking dataset***

For fishing data in which the spatial distribution of the animal may be

heterogeneous, the negative binomial distribution often fits the data well (Hilborn

1985). There are four justifications for using a negative binomial regression

model in this specific case:

1. The data are counts.

2. The negative binomial regression model is used instead of the Poisson,

for there is evidence of overdispersion of the data, in which the variance of

the counts far exceed the means (Table 1.1).

3. The relationship between the mean and variance follows the pattern of

a negative binomial regression model (Figure 1A.2).

58

4. Since animals often are not randomly distributed but clustered, the negative binomial regression model takes into account spatial variability.

Development of a more parsimonious model for Core Sound (negative binomial regression with seasonality model)

There are three observations that lead to the creation of a new model for Core Sound. Since this method is *ad hoc* (as opposed to *a priori* for the previous model) here is a list of the three ideas that support the usage of this model.

1. There is a seasonal pattern to the clam catches (Figure 1.3). Both COC and CO yield higher clam catches in fall than spring. A seasonality effect is incorporated (perhaps different ones for COC and CO).

2. Whereas clam catches increase with time for both COC and CO, there is an overall greater increase in COC. A regression model that incorporates time is used.

3. COC and CO have separate lines with different slopes, so the need for different intercepts is also tested.

A simple model is constructed in which COC and CO have the same intercepts and seasonality effect. Here is the model:

$$CO = \log \mu = \beta_0 + \beta_1 * Date + \beta_2 * Season$$

$$COC = \log \mu = \beta_0 + (\beta_1 + \beta_3) * Date + \beta_2 * Season$$

After applying the same analysis to the parsimonious model, I find that the AIC_c value is smaller than that of the main model. All effects are highly significant (date, season, date/treatment). Of particular importance is that the rate of

59

increase in the clam catch over time is predicted to be significantly greater in

COC than in CO. Figure 1.5 depicts mean clam catches at each sampling period

for COC and CO, based on the parsimonious negative binomial regression with

seasonality model. The predicted means are close to the observed means,

suggesting a good fit. For the goodness-of-fit test, the Pearson chi-square is

applied to cell counts of six or greater and the fit is remarkable (Figure 1A.5).

Part 2. Synopsis of development of a model for legal clam populations in Pamlico Sound

For Pamlico Sound, since there are zero counts, a constant (k=0.5) is

added to each y. Also, both lognormal and negative binomial distributions fit the

data (Figure 1A.6). Figure 1.6 depicts the number of legal-sized clams obtained

in individual trawl samples in PCO and PC for all six sampling periods. Table 1.5

contains the means and variances of the clam catches in PCO and PC for all six

sampling periods. Before the plan, PCO and PC are fairly different, but both

could produce large catches. After the implementation of the plan, the mean

trajectories initially diverge, but then converge at the last sampling period. Also,

after the plan started, large catches are found only in PC.

As in Core Sound, the positive relationship between the mean and the

variance is typical for count data and is addressed by the model. Next the mean-

variance relationship is quantified. The Pamlico Sound data are reasonably fit by

binomial and lognormal models. These data are heteroscedastic so Poisson

models are not used. The negative binomial model is used because it worked

well with the Core Sound data. Since in Core Sound lognormal models are not

useful and to apply them to Pamlico Sound requires additional calculations, they are not used. More calculations also are necessary for square-root transformed models, and normal models do not have the best fit, so only negative binomial regression models are used. Akaike weights are used to determine which fit the best at each sampling period (Table 1A.7). These results provide strong evidence that the mean number of legal clams per trawl in PCO and PC immediately diverge but then this difference becomes less important over time.

The 95% confidence interval for the mean ratio of PCO to PC is used to determine the direction of the difference (Table 1.7). These confirm the AIC_c rankings of the models. When both PCO and PC are closed, their mean ratio is not different from one. The results are dramatic: after PCO is opened, the mean number plummet relative to the number in PC. In spring and fall 2002, the catch in PC is 2 to 10 times larger than that in PC. In spring 2003 the catch in PC is 1.2 to 10 times larger than in PC (but the mean ratio was still different from one). However, by fall 2003, the mean number of clams is larger in PCO than PC (but not significantly larger). The model fit to for Pamlico Sound is the best negative binomial regression at each sampling period (Figure 1.7). Although the catches in Pamlico vary considerably more during the course of the study than in Core Sound, in PCO by the end of the study, the catches are on average 75% of the original catches, and in PC they are only 20% of the original catches.

Chapter 1 Appendix. Figures.
The effects of rotating Marine Protected Areas (MPAs) on the productivity of the North Carolina hard clam (*Mercenaria mercenaria*) fishery.

Figure 1A.1. Distribution of legal clam catches for 185 samples taken in COC and CO during the six sampling periods. Negative binomial and lognormal density estimates (using maximum likelihood) were superimposed on the histogram. Bin width refers to the degree of smoothing; the higher the bin width, the greater the degree of smoothing. Since both distributions provided a reasonable fit, normal-based models did not apply to these data.

Core Sound: Overall Distribution of Legal Clam Catches
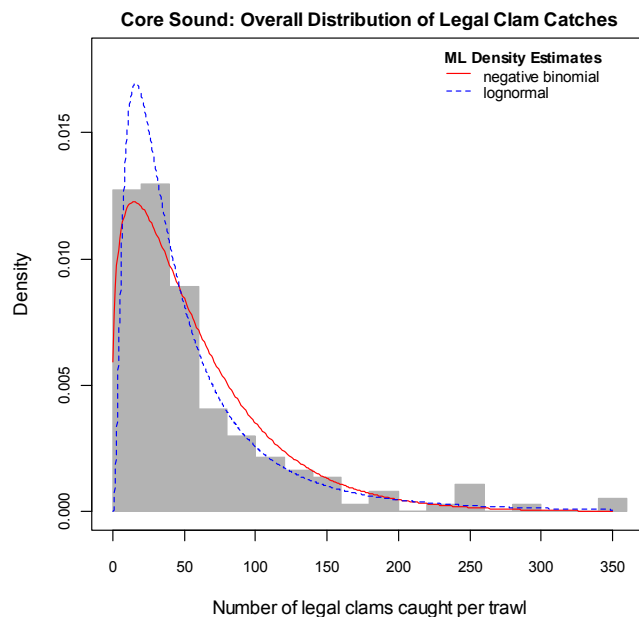
Table 1A.1. Theoretical mean-variance relationships for various probability models. Least squares regression was used to test for homogeneity by determining which of these probability models matched the mean-variance relationship of the data.

Probability Model	Mean-Variance Relationship
Poisson	$\sigma^2 = \mu$
Scaled Poisson	$\sigma^2 = k\mu$
Negative binomial	$\sigma^2 = \mu + \dfrac{\mu^2}{k}$
Lognormal	$\sigma^2 = \kappa\mu^2$
Gamma	$\sigma^2 = \alpha\mu^2$

Figure 1A.2. Mean-variance relationship for legal-sized clam catches in COC and CO. The twelve points represent the six sampling periods of COC and CO.

Core Sound: Mean-Variance Relationship for Legal Clam Catches
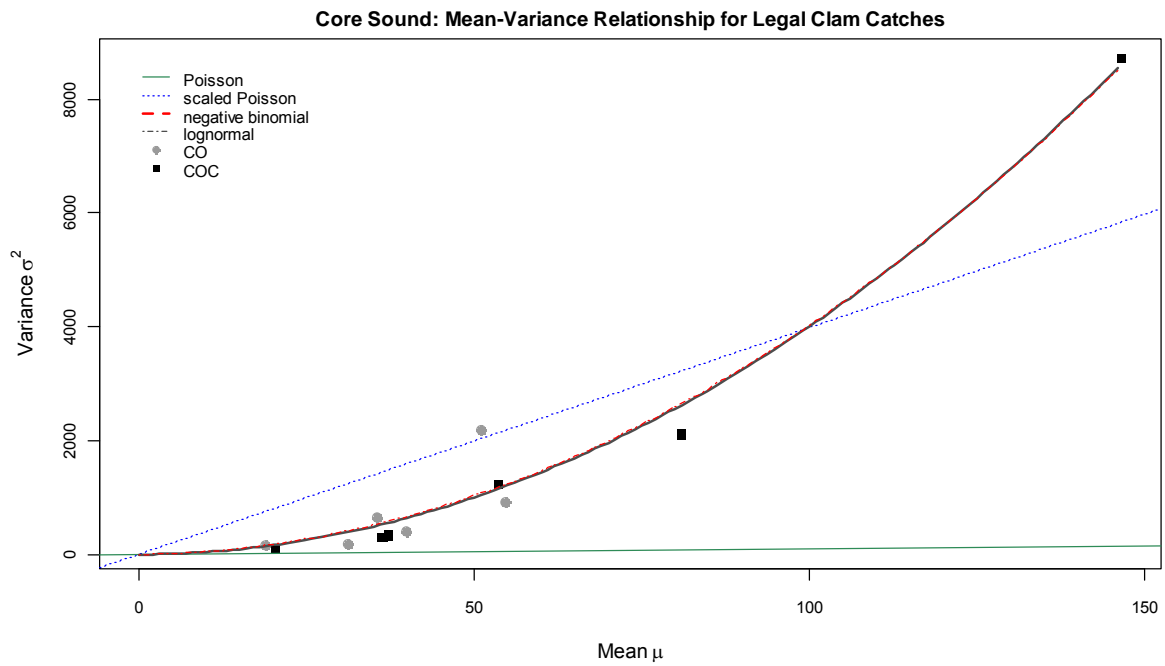
Table 1A.2. The four classes of models that were used to fit the data.

Class of Model	Error Distribution	Response
Standard linear	Normal	Number of legal clams
Standard linear	Normal	Log-transformed number of legal clams
Standard linear	Normal	Square-root transformed number of legal clams
Generalized linear	Negative binomial	Number of legal clams and a log link

Table 1A.3. The two versions of each model listed in Table 1.3.

Model Assumption	Terms for Variables Included
Mean was the same for COC and CO	Intercept
Mean differed for COC and CO	Intercept and treatment

Table 1A.4. The four negative binomial regression models that were fit to the data.

Model Assumption	Variables Included
Same mean and dispersion for COC and CO	Intercept
Same mean, different dispersion for COC and CO	Dispersion
Same dispersion, different mean for COC and CO	Treatment
Different mean and dispersion for COC and CO	Treatment and dispersion

Table 1A.5. The model with the best (least) AIC_c value and best (highest) Akaike weight value for each sampling period for Core Sound.

Sampling Period		AIC_C-best Model
2001	Spring	Negative binomial: intercept
	Fall	Negative binomial: dispersion
2002	Spring	LogNormal: intercept
	Fall	Negative binomial: treatment & dispersion
2003	Spring	Negative binomial: intercept
	Fall	Negative binomial: treatment

Table 1A.6. The model with the highest Akaike weights fit separately for each sampling period for only the negative binomial models.

Sampling Period		Akaike Weight-best Model (all negative binomial)
2001	Spring	Intercept
	Fall	Dispersion
2002	Spring	Intercept
	Fall	Treatment & dispersion
2003	Spring	Intercept
	Fall	Treatment

Figure 1A.3. Plot of the best Akaike weights for only the negative binomial models.

Core Sound: Best Akaike Weights for Negative Binomial Models of Legal Clams
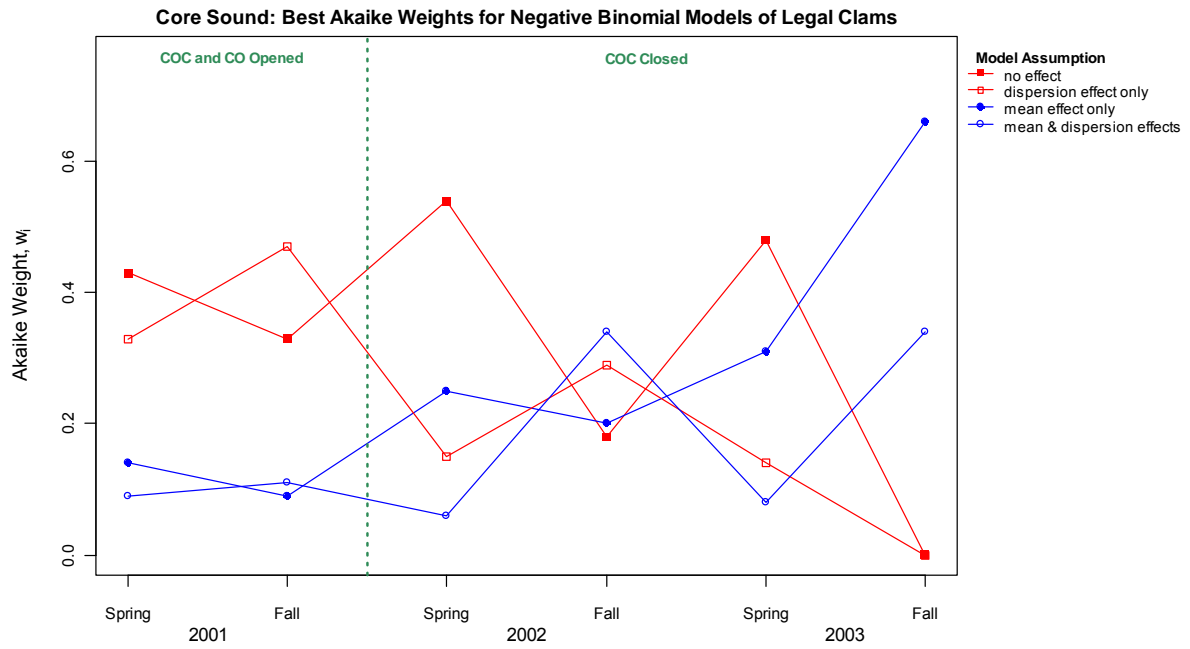
Figure 1A.4. Expected and observed cell probabilities for legal clam catches in Core Sound for the negative binomial regression model. All expected cell counts were six or greater.

Core Sound: Original Negative Binomial Regression Model Goodness-of-Fit
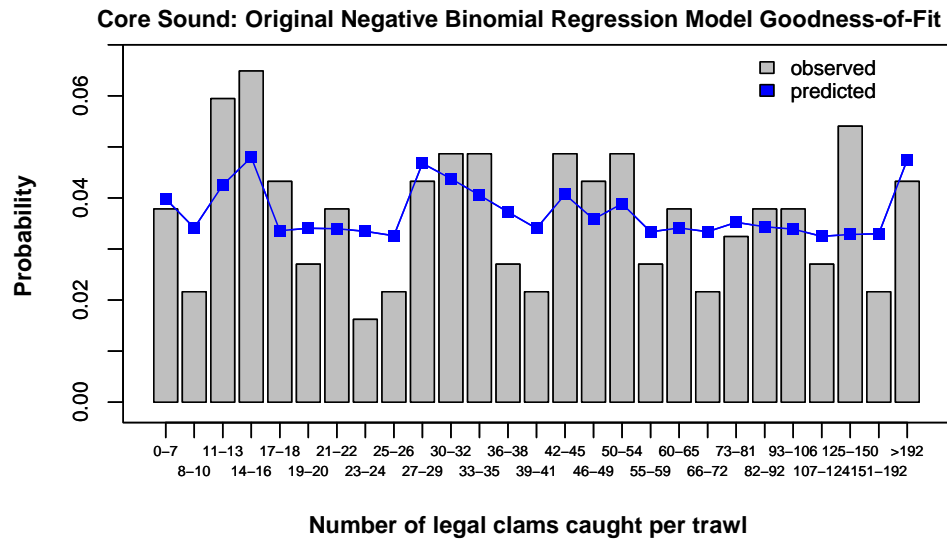
Figure 1A.5. Expected and observed cell probabilities for legal clam catches in Core Sound for the parsimonious negative binomial regression with seasonality model. All expected cell counts were six or greater.

Core Sound: Parsimonious Negative Binomial Regression
w/Seasonality Model Goodness-of-Fit

Number of legal clams caught per trawl
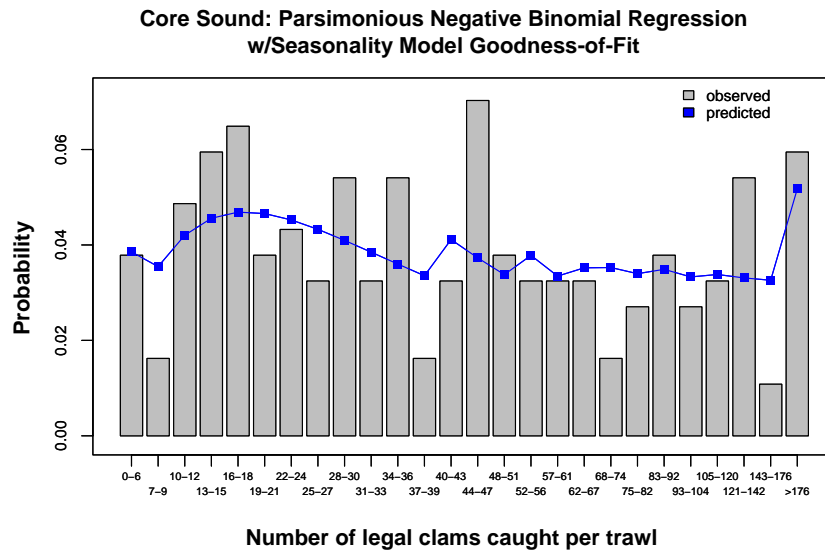
Figure 1A.6. Distribution of legal clam catches for 201 samples taken in PCO and PC during the six sampling periods. Negative binomial and lognormal density estimates (using maximum likelihood) were superimposed on the histogram. Similar to Core Sound, both distributions provided a reasonable fit to the data.
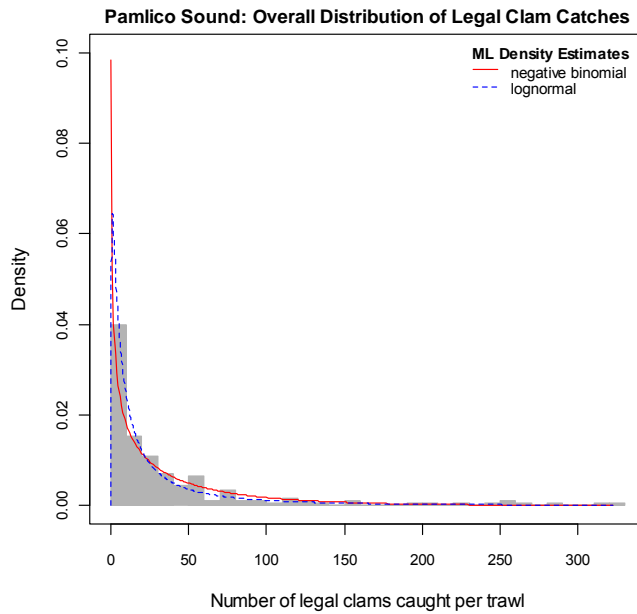
Table 1A.7. The model with the highest Akaike weights fit separately for each sampling period for only the negative binomial models.

Sampling Period		Akaike Weight-best Model (all negative binomial)
2001	Spring	All four equivalent
	Fall	Dispersion
2002	Spring	Treatment
	Fall	Treatment
2003	Spring	Treatment
	Fall	Treatment, treatment and dispersion

Figure 1A.7. Expected and observed cell probabilities for legal clam catches in Pamlico Sound for the negative binomial regression. All expected cell counts were five or greater. The samples from spring 2002, fall 2002 and spring 2003 were combined before calculating parameter estimates.
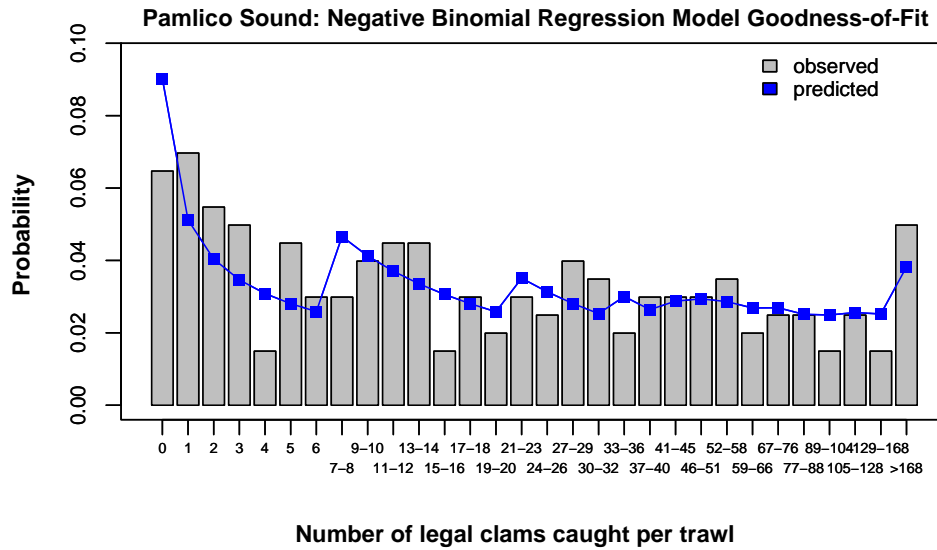
Literature Cited

(NRC) N. R. C. 1999. Sustaining Marine Fisheries.

Botsford, Louis W., Castilla, Juan Carlos, Peterson,Charles H. 1997. The management of fisheries and marine ecosystems. Science **277**:509-514.

Botsford, Louis W., Micheli, Fiorenza,Hastings, Alan. 2003. Principles for the design of marine reserves. Ecological Applications **13**:S25-S31.

Gerber, Leah R., Botsford, Louis W., Hastings, Alan, Possingham, Hugh P., Gaines, Steven D., Palumbi, Stephen R.,Andelman, Sandy. 2003. Population models for marine reserve design: a retrospective and prospective synthesis. Ecological Applications **13**:S47-S64.

Guthrie, James F., Lewis,Curtis W. 1982. The clam-kicking fishery of North Carolina. Marine Fisheries Review **44**:16-21.

Halpern, Benjamin S., Warner,Robert R. 2002. Marine reserves have rapid and lasting effects. Ecology Letters **5**:361-366.

Halpern B. S. 2003. The impact of marine reserves: do reserves work and does reserve size matter? Ecological Applications **13**:S117-S137.

Lubchenco, Jane, Palumbi, Stephen R., Gaines, Steven D., Andelman,, Sandy. 2003. Plugging a hole in the ocean: the emerging science of marine reserves. Ecological Applications **13**:S3-S7.

Pauly, Daniel, Christensen, Villy, Guenette, Sylvie, Pitcher, Tony J., Sumaila, U. Rashid, Walters, Carl J., Watson, R.,Zeller, Dirk. 2002. Towards sustainability in world fisheries. Nature **418**:689-695.

Pauly D.,Watson. 2003. Counting the last fish. Scientific American **289**:42.

Peterson C. H. 2002. Recruitment overfishing in a bivalve mollusc fishery: hard clams (Mercenaria mercenaria) in North Carolina. Can.J.Fish.Aquat.Sci. **59**:96-104.

Rieser A. 2000. Essential fish habitat as a basis for marine protected areas in the U. S. exclusive economic zone. Bulletin of Marine Science **66**:889-899.

Roberts, Callum M., Andelman, Sandy, Branch, George, Bustamante, Rodrigo H., Castilla, Juan Carlos, Dugan, Jenifer, Halpern, Benjamin S., Lafferty, Kevin D., Leslie, Heather, Lubchenco, Jane, McArdle, Deborah, Possingham, Hugh P., Ruckelshaus, Mary, Warner,Robert R. 2003. Ecological criteria for

evaluating candidate sites for marine reserves. Ecological Applications **13**:S199-S214.

Roberts, Callum M., Hawkins, Julie P., Gell,Fiona R. 2005. The role of marine reserves in achieving sustainable fisheries. Phil.Trans.R.Soc.B. **360**:123-132.

Chapter 2:
Effects of Clam Kicking Disturbance on Seagrass Populations in Core and Pamlico Sounds

INTRODUCTION

Lotze *et al.* (2006) reconstructed baseline datasets regarding abundances of seagrasses at the time of human settlement in 12 estuaries and coastal seas in Europe, North America and Australia and estimated that human activities have since eliminated 65% of seagrass populations. In 2003, the World Conservation Monitoring Centre of the United Nations Environment Programme (UNEP) published the World Atlas of Seagrass. In the first study of global seagrass coverage, UNEP discovered that 15% of the vegetated area had disappeared during the 1990's and early 2000's. In the early 1990's, there were approximately 208,000 km^2 of seagrass coverage worldwide. A 2003 estimate is 177,000 km^2 (Green and Short 2003). Seagrass may recede quickly; Short *et al.* (2006) documented seagrass declines in one- to two-year periods while sampling five sites in North and South America.

Seagrass beds provide numerous benefits to the functioning of coastal ecosystems. They are composed of high standing biomass and support high rates of production. The ecosystem does not entirely consume this production, because a portion of it is retained in the sediment or transferred to adjacent

areas (Duarte 1999). Seagrass meadows also enhance water quality by removing particles and dissolved nutrients from the water. Additionally, they stabilize the seafloor and protect the shoreline by both binding the sediment with their roots and diminishing flow (Hemminga and Duarte 2000, Thayer *et al.* 1997).

Seagrass beds create an intricate and dynamic system of food and refuge, providing primary nursery areas for ecologically-important and commercial and recreational fishery and shellfishery species. For instance, seagrass beds contain many sources of organic carbon to supply food for vertebrates and invertebrates. Seagrasses produce organic matter that is consumed by herbivores, detritivores and microorganisms.

Hemminga and Duarte (2000) reviewed 24 studies in which virtually all found higher species diversity and abundances of fish, decapods and benthic fauna in seagrass than in nearby unvegetated bottom. (Orth *et al.* J. 1984) discovered that fish and invertebrates are less likely to be preyed upon in seagrass beds and conversely, predators are less likely to be successful. This results from lower visibility of prey and impeded motion of the predator.

Disturbance of seagrass

Seagrass beds are labeled as "valuable but vulnerable" members of coastal communities (Hemminga and Duarte 2000). Although seagrass is adapted to

withstand moderate disturbance due to its evolution in a variable environment, the level of disturbance that currently exists in most coastal areas is too extreme for most seagrass species.

Natural events can cause declines in seagrass populations. These include earthquakes, eruptions, hurricanes, consumption by animals, and wasting disease (a type of slime mold) (Hemminga and Duarte 2000). For example, in the 1930's, there was an epidemic of wasting disease that destroyed 90% of an Atlantic eelgrass (*Zostera marina*) population, negatively affecting it for decades (Fonseca *et al.* 1984).

Human disturbance is the major cause of damage to seagrass populations. Short and Wyllie-Echeverria (Short 1996) researched more than forty sites composed of shrinking seagrass populations and found that human disturbances caused the declines greater than 70% of the time. There are many types of anthropogenic disturbance. Most likely, the main cause of seagrass decline is a decrease in water clarity. This decrease results from two factors: eutrophication due to the widespread use of fertilizers and other forms of pollution and sedimentation from global population growth, which initiates deforestation, erosion and siltation (Green and Short 2003). Seagrasses are superior competitors to algae in low nutrient water because they store nutrients in their biomass that can be utilized when necessary (Hemminga and Duarte 2000). However, in limited light conditions that result from increased POM, DOM, and sedimentation, microalgae and most macroalgae can outcompete seagrass. Several factors cause this: seagrasses are benthic and cannot capture light as

well as algae that are suspended in the water column, light absorption is much more efficient in algae than in seagrass, and seagrasses have to support below-ground biomass consisting of roots and rhizomes. As a result, impaired underwater light availability decreases seagrass production and induces hypoxia or anoxia in the below-ground biomass.

Death of seagrass triggers an escalating cycle in which denuded sediment becomes resuspended because it is exposed to currents and is no longer secured by seagrass vegetation, which in turn blocks more light. Continuing plant mortality lowers oxygen in the sediments. Additionally, the high nutrient loads in eutrophic waters lead to more nutrient-dense and therefore more palatable seagrass and algae, attracting more herbivores that eat more plants (Hemminga and Duarte 2000). Aquaculture facilities can pollute coastal waters by surplus feed and fish waste. Direct injury of the plant is also a common threat. Extensive use of small boats may cause seagrass mortality due to propeller scars (Walker 1989, Creed *et al.* 1999). Although disturbance can be caused by boating, anchoring, and dredging and filling, my study focuses on the effects of commercial fishing gear.

Disturbance of seagrass by fishing gear

The usual consensus of fishery biologists and managers is that habitat degradation is the principal threat for sustainable fisheries (Stephan *et al.* 2000). Mechanical harvesting practices that come in contact with the sediment are detrimental to seagrass beds. They injure both vertical and horizontal rhizomes,

which have roots and meristems, or may detach the entire plant from the bottom (Hemminga and Duarte 2000). De Jonge and De Jong (1992) performed a study in the Netherlands in which they found that fishing gear used in mollusk fisheries partially caused seagrass declines and prevented their recovery. Fonseca *et al.* (1984) found severe reductions in seagrass populations due to scallop harvesting.

Stephan *et al.* (2000) listed five characteristics of seagrass that are vulnerable to destruction by fishing gear. The first four involve physical disturbance of the plant, the fifth concerns water quality, and I've added one more.

1. The vegetative structures (both above and below the sediment) may be uprooted or chopped. Damage to the plant beneath the sediment is particularly harmful, as the underground rhizomes have roots (which anchor and sustain the plant) and meristems (which are sites of growth). Damage to meristems is serious as this can prevent growth or asexual reproduction for the season or may kill the plant.

2. Sexual reproduction may be inhibited if the seeds or flowers are sheared by the gear. This will affect the amount of seagrass that grows in the upcoming year.

3. Vegetative (clonal) spread depends on intact plant structures as well.

4. The substrate type affects the extent of damage to the plant. Fonseca *et al.* (Fonseca *et al.* 1984) studied the effects of bay scallop dredging on seagrass. In mud, plants were uprooted and the roots and rhizomes

injured. In sand, the majority of damage occurred in the above-ground

biomass, but repeated dredging over time can damage the entire plant.

5. Burial by sediments reduces or eliminates the plant's ability to

photosynthesize by covering leaves.

6. Seagrass "seed banks" in which seeds are dormant in the sediment

may be disturbed, especially in the winter.

The effects of clam kicking on seagrass

Mechanical clam harvesting or "clam kicking" for the hard clam,

Mercenaria mercenaria, greatly disturbs the sediment in several ways (Guthrie *et*

al. 1982). Although there are variations, the gear that I used for clam kicking

sampling had four components that were dragged directly across the sediment.

These included a large metal cage that collects the clams, a net that is held open

and flush with the bottom of the seafloor with a heavy metal chain, and two

wooden "otter trawl" doors. The net funnels the "kicked" clams into the cage.

Additionally, the propeller is adjusted for kicking by directing the wash into the

sediment to dislodge the clams. Clam kicking can potentially impact the

seagrass populations in all of the seven ways listed above.

Quantitative data on recovery of seagrass beds from disturbance are few

(Stephan *et al.* 2000). One study that is directly related to this paper was done

by Peterson *et al.* (1987). Six, 1225-m^2 plots were located in each of two

shallow estuarine habitats, seagrass beds and sand flats. The researchers

tested the impact of different intensities of clam harvesting, including kicking, on

density of *M. mercenaria* recruits (length < 2.5 cm) and seagrass biomass for up to four years. The effects of kicking on density of clam recruitment were unclear. However, intense kicking had a large effect on seagrass biomass. All levels of clam harvest quickly decreased biomass and this decrease was greater with greater intensity. With lower intensities of harvesting, seagrass biomass returned to the amount predicted by the control within a year. High intensity (which was most likely lower than that of the intensity of commercial clammers) decreased seagrass biomass by approximately 65% relative to levels expected from controls. Recovery of seagrass biomass did not begin until two years had passed. After four years, the biomass was still approximately 35% lower than predicted from controls. The authors concluded that if a certain level of seagrass mortality occurs, then the population will be slow to return. The results of this study led to a clam kicking ban in seagrass beds in NC.

The current study aims to build upon this research by studying the issue on a large scale. I did not expect to find seagrass in opened areas because of the kicking ban. However, I collected it in my kicking gear, so I investigated changes in seagrass populations associated with implementation of the rotation plan. I studied areas that were never exposed to kicking, continuously kicked, previously exposed to kicking and then protected, and previously protected and then kicked.

Investigation of the effects of the clam kicking rotation plan on seagrass populations

Declining catches of *M. mercenaria* by clam fishermen or "clam kickers" in Core Sound, Carteret County, NC, led the North Carolina Division of Marine Fisheries (NCDMF) to institute a mechanical clam harvesting area rotation plan for two years beginning in the fall 2001 season (NCDMF Hard Clam Fishery Management Plan, October 2000). Approximately 4500 acres of an overharvested area in northern Core Sound was closed and a previously unharvested area of similar size in southeastern Pamlico Sound was opened for two mechanical clam harvesting ("clam kicking") seasons. My research project was to determine if the productivity of the hard clam fishery in central NC increased after implementation of the rotation plan. In North Carolina, because clam kicking is banned in seagrass beds as a result of Peterson *et al.* (1987). I did not expect to find seagrass in any of the clam kicking areas. However, I found it from the beginning of the study in both Core and Pamlico Sounds, so I collected qualitative, ordinal data describing the samples. *Zostera marina*, or eelgrass, is found in the spring and *Halodule wrightii*, or Cuban shoalgrass, is found in the fall (Figs. 2.1 and 2.2). I analyzed how the abundances of these two species changed in relation to alterations in clam kicking disturbance as a result of the rotation plan.

Virtually the entire period of sexual reproduction and one-third to one-half of the period of vegetative reproduction of *Z. marina* overlaps with the clam kicking season (Figure 2.3). Although both *Z. marina* and *H. wrightii* are perennial in NC, I predict that in areas protected from kicking, *Z. marina* will exhibit greater increases in abundance over time than *H. wrightii*. Negative

above-ground impacts of clam kicking including leaf/flower shear and plant burial are greater on *Z. marina* than on *H. wrightii* in opened areas, because the above-ground portions of *H. wrightii* are not present during the clam kicking season. Although clam kicking may tear up below-ground parts (roots and rhizomes) as well, the impacts on the above-ground portions should be greater because they are subject to higher exposure to disturbance.

METHODS

I divided the study areas in Core and Pamlico Sounds into four treatments (Figure 2.4). Core-Opened-Closed (COC) is the traditionally productive area in Core Sound that was closed for two years beginning in the clam kicking season of December 2001 to March 2002. Core-Opened (CO) remained opened and is the harvested control. Pamlico-Closed-Opened (PCO) is the previously unharvested area that was opened for two years as a substitution for COC so that clammers would have access to clamming grounds covering a similar area. Pamlico-Closed (PC) is my unharvested control. It is the only area in southeastern Pamlico Sound that is permanently closed (due to the presence of seagrass) yet also accessible by both clam kicking boat and gear to me by scientific collection permit. After the kicking plan was implemented, I checked with NCDMF multiple times to ensure that there was no illegal kicking occurring in PC and I was told that there was none (Murphey pers. comm.). My impact on the area was minimal compared to that of an area opened to commercial kicking.

There were six sampling periods, one each in spring and fall during the years of 2001, 2002 and 2003 (Figure 2.5). I covered each of the four treatment areas as extensively as possible, resulting in a minimum of twelve trawls per treatment. After each five-minute trawl I counted the legal (width equal to or greater than one inch or 25.4 mm) and larger sublegal clams harvestable by kicking gear (approximately 0.75 inches or 19mm in width) to calculate the mean number of clams caught per trawl. When seagrass was incidentally collected by the clam kicking cage, I estimated the amount found in each trawl on an ordinal scale: absent (A), low (L), moderate (M) and high (H). I found *Z. marina* exclusively in the spring and *H. wrightii* in the fall. I did not find roots and rhizomes of *H. wrightii* caught in the cage during the spring or *Z. marina* roots and rhizomes in the fall.

ANALYSIS AND RESULTS

The spring (*Z. marina*) samples from COC and CO were analyzed first. In this section I include the dichotomization of the data into high-low categories. Additional analyses and justification for the use of the one described here are included in Appendix 2.

Dichotomizing the spring (*Z. marina*) data from Core Sound into high-low categories

Table 2.1 shows the distribution of seagrass (*Z. marina*) scores for the spring 2001, 2002 and 2003 sampling periods for Core Sound, summarized by

the number of trawls with seagrass over time separately for the two treatment areas. Scoring schemes that weighted the high category most heavily provided greater discrimination between COC and CO (Appendix 2). This suggested that the high category alone was driving the results. Therefore, I divided the data into high (H) and low (L) categories, in which low equalled A+L+M (Table 2.2). Both COC and CO started with a low percentage of trawls in the H category and then the two regions diverged. In COC the percentage of high trawls increased over time, while in CO it remained low.

Paralleling the methodology for analyzing the presence-absence dichotomy (Appendix 2), Figure 2.6 displays the Clopper-Pearson mid-P confidence interval. In 2001, COC and CO were not significantly different from one other. By 2002, they diverged, but the difference was not significant. By 2003, COC and CO have become significantly different from each other. To test whether the differences in proportions of COC minus CO have significantly increased with time, a 95% bootstrap confidence interval was constructed for the effect score using 10,000 bootstrap samples. The effect score was 0.454 with a 95% bootstrap percentile confidence interval of (0.136, 0.772). Since this interval does not include zero, the proportion of trawls returning a high density of *Z. marina* increased in COC relative to CO during the course of the study. This high-low analysis was consistent with results obtained using all four categories which were assigned numerical scores, because scoring systems that weighted the higher categories more heavily tended to yield larger differences over time (Appendix 2).

The series of analyses described in Appendix 2 is repeated for the remaining sample periods and locations. The results of the high-low dichotomy analyses are summarized in the following sections.

Analysis of fall (*H. wrightii*) samples from Core Sound

Table 2.3 shows the distribution of seagrass (*H. wrightii*) scores for the fall sampling period for Core Sound, summarized by the number of trawls with seagrass over time separately for the two treatment areas. Clopper-Pearson Mid-P confidence intervals were mapped on a graph depicting the proportion of trawls with scores of high as a function of time (Figure 2.7). The overall effect score was not significant, so there was no evidence for a change in the presence of high density trawls of *H. wrightii* in COC versus CO from 2001 to 2003.

Analysis of spring (*Z. marina*) samples from Pamlico Sound

Table 2.4 contains the distribution of seagrass (*Z. marina*) scores for the spring sampling period for Pamlico Sound, summarized by the number of trawls with seagrass over time separately for the two treatment areas. Clopper-Pearson Mid-P confidence intervals were mapped onto a graph depicting the proportion of trawls with scores of high as a function of time (Figure 2.8). The overall effect score was not significant for so there is no evidence for a change in the presence of high density trawls of *Z. marina* in PCO versus PC from 2001 to 2003.

Analysis of fall (*H. wrightii*) samples from Pamlico Sound

Table 2.5 shows the distribution of seagrass (*H. wrightii*) scores for the fall sampling period for Pamlico Sound, summarized by the number of trawls with seagrass over time separately for the two treatment areas. Clopper-Pearson Mid-P confidence intervals were mapped onto a graph depicting the proportion of trawls with scores of high as a function of time (Figure 2.9). The overall effect score was not significant so there was no evidence for a change in the presence of high density trawls of *H. wrightii* in PCO versus PC from 2001 to 2003.

DISCUSSION

As depicted in Figure 2.3, the majority of the time period that *Z. marina* is sexually reproducing and approximately half of the time period of vegetative growth and clonal reproduction, and therefore the peak period of above-ground biomass, occur during the clam kicking season. Although the proportion of trawls with high density seagrass (*Z. marina*) was very similar in spring 2001 in COC and CO, after the protected area (COC) was established in winter 2001, by spring 2002, this proportion was higher in COC than CO. This difference increased over time, becoming significantly different by 2003. The peak of above-ground biomass of *H. wrightii* does not coincide with the clam kicking season. There was no change in the presence of *H. wrightii* in COC relative to CO during the course of the study. I conclude that clam kicking does not eliminate *Z. marina* from the habitat, but reduces its overall population density

resulting in less seagrass per trawl. After two harvesting seasons of protection

from clam kicking, the overall density of *Z. marina* increased in the protected

area (COC) relative to the opened area (CO). *Z. marina* is affected more than *H.*

wrightii because the above-ground biomass of *Z. marina* peaks during the kicking

season and is subject to greater impacts of disturbance, including leaf/flower

shear, uprooting and burial, while the below-ground biomass of *H. wrightii* is

protected by a layer of sediment. I never found roots and rhizomes of *H. wrightii*

in the spring or of *Z. marina* in the fall.

Although both PCO and PC were fully protected in 2001, I found only one

high density sample of *Z. marina* in PC. In spring 2002 and 2003, in both PCO

and PC, there were very few (3 total) high density (*Z. marina*) trawls and there

were no significant differences between the two treatments over time. In fall

2001, in both PCO and PC, there were no high density trawls of *H. wrightii*. After

PCO was opened, in fall 2002 and 2003 the number of high density trawls of *H.*

wrightii increased in both PCO and PC relative to 2001. There was no significant

difference in the increases between the two areas. Therefore, I did not find a

quantifiable effect of the clam kicking rotation plan on the seagrass populations

(both species) in Pamlico Sound.

There is debate about whether or not NCDMF may have closed off

locations of seagrass near the boundaries of kicking areas before the kicking

season. This may have affected the results of this study if the seagrass areas

along the edges of COC that would have normally been closed off to fishermen

weren't during the rotation plan but continued to be marked off in CO. Further

research of exactly what is done by NCDMF and accompanying data including dates, locations and type of marking are necessary in order to establish exactly how this may change the analysis. Presumably, the direction of bias is a confounding one. The bias is unlikely to be large enough to explain the pattern I found, for I sampled across entire treatment areas and rarely was close to the NCDMF markers of the boundaries, so a very small proportion of my trawls were near the edges of the areas which would have been marked off by the buoys in a regular season if they contained seagrass.

Data quantifying the recovery of seagrass after disturbance are few because of the multitude of factors involved. Stephan *et al.* (2000) developed a scale ranking the ability of different seagrass species to recover from disturbance. This scale was based upon previous studies, including Peterson *et al.* (1987) and Fonseca *et al.* (1998), as well as the experience of the authors. The authors assessed the ability of seagrass species to recover from damage to meristems and reproductive structures and placed them into three categories describing their potential to recover from disturbance: low, moderate and high. In this assessment, *H. wrightii* was labeled as having "high recovery potential" and *Z. marina* was categorized as having "moderate recovery potential". The structure and ecology of each of the two species can be analyzed to determine why they have differences in resiliency.

Z. marina is a cosmopolitan species found in the northern Atlantic, Mediterranean, and west and east Pacific, so it has been well-studied (Hemminga and Duarte 2000). In North Carolina, *Z. marina* (as well as *H.*

wrightii) is a perennial plant that is slow to colonize new bottom (Fonseca *et al.* 1984). If *Z. marina* were annual (as it is in some places) the damage to the plant structure from kicking would not be as severe, for it would be replaced by an entirely new plant the following year. However, in perennial *Z. marina* (which is found in NC) physical injury is enduring because it can only moderately recover from damage and relies heavily on sexual reproduction (Stephan *et al.* 2000).

Approximately 95% of the pollen of *Z. marina* is retained within a 15 m radius. The seeds are buoyant, with 95% of the seeds remaining within 30 m of the source, and in Chesapeake Bay, 80% being retained within 5 m (Hemminga and Duarte 2000). Therefore, the plants are surrounded by pollen and seeds and also are affected by kicking. The seeds can remain dormant in the sediment for one to two months, building a temporary seed bank. Additionally, burial of the seeds too deeply within the sediment prevents them from germinating (Hemminga and Duarte 2000). There are several components of the kicking gear that can destroy seed banks as well as bury seeds. Since approximately 65% of *Z. marina* seeds are already lost to predation (Hemminga and Duarte 2000) additional losses can be devastating to a population.

H. wrightii is a member of the Caribbean flora, is perennial and is found as far north as NC (Hemminga and Duarte 2000). *H. wrightii* has high recovery potential because it spreads by vegetative growth at higher rates than *Z. marina*. Little is known about its sexual reproduction. It has done well in restoration(Stephan *et al.* 2000). It is considered a pioneer species and is most tolerant to high salinity and temperature ranges and UV radiation (Thayer *et al.*

1981). On average across a variety of environmental conditions, a rhizome grows in only 6 d, compared to 15 d in *Z. marina*. Also, the life span of a leaf is only 30 d, whereas in *Z. marina* it is 90 d (Hemminga and Duarte 2000). *H. wrightii* is better adapted to disturbance due to quicker growth and shorter life spans of its structures.

Selective removal of one species of seagrass from the estuary can have great repercussions on the ecosystem. If the loss to a seagrass population is great enough, clones may not be sufficient to restore the population and sexual reproduction becomes vital, yet due to large seed losses it is very risky (Hemminga and Duarte 2000). Disrupting the balance of the seagrass populations could lead to altered ecosystem functioning. For instance, some species provide better habitat than others due to structure and functioning (Fonseca *et al.* 1984). Kicking could be destroying an old seagrass population that has maintained this ecosystem for long time. For instance, in the Baltic Sea there are meadows comprised of *Z. marina* that are one-thousand years old (Reusch *et al.* 1999).

If *Z. marina* is removed from an area where it is the only seagrass, the area can become a sandflat. Peterson *et al.* (1987) suggest that sand flats and seagrass beds may be alternative stable states, so that the area's return to seagrass habitat may need a large amount of energy input. Therefore, the removal of seagrass may have long-lasting effects.

Seagrass has variable effects on the growth of *M. mercenaria*. Peterson *et al.* (1984) and Irlandi and Peterson (1991) found that seagrass increases clam

growth, possibly because of increased particle settlement or decreased sediment resuspension. Peterson and Beal (1989) found that seagrass inhibited or had no effect on growth. The growth inhibition may be due to the decreased flow caused by seagrass, resulting in reduced availability of food particles and increased mud collection. However, clam population density is often higher in more complex habitats with seagrass or shell.

Clam recruitment may be affected by kicking and removal of seagrass. If seagrass beds are subjected to strong waves or currents, larvae and juveniles of fish and shellfish may be dislodged or killed (Jenkins *et al*. 1997). This cycle of reduced recruitment continues with the recruits in the following season, due to reduced complexity of habitat caused by loss of seagrass.

Chapter 2 Figures.
Effects of Clam Kicking Disturbance on Seagrass Populations in Core and Pamlico Sounds.

Figure 2.1. *Zostera marina*, or eelgrass, one of the two dominant species of seagrass found in the study area. Although *Z. marina* is perennial in NC, the above-ground biomass peaks in the spring. Note that this photo was not taken in NC.

Figure 2.2. *Halodule wrightii*, or Cuban shoalgrass, one of the two dominant species of seagrass found in the study area. Although *H. wrightii* is perennial in NC, the above-ground biomass peaks in the fall.

Figure 2.3. Diagram of the overlap of clam kicking season with vegetative/clonal growth and reproduction of the two species of seagrass. Note that the entire clam kicking season occurs during periods of growth and reproduction for *Z. marina*, whereas there is no overlap for *H. wrightii* (diagram by author, species information from Stephan *et al*. 2000).
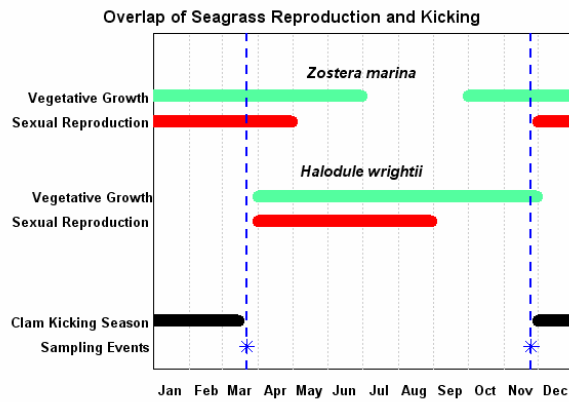
Figure 2.4. Map of the study area in Carteret County, NC, with marked treatment areas.

Mechanical Clam Harvesting Rotation Plan: Treatment Areas

Pamlico Sound

Study Site

Core Sound

PCO

PCO

PC

COC

CO
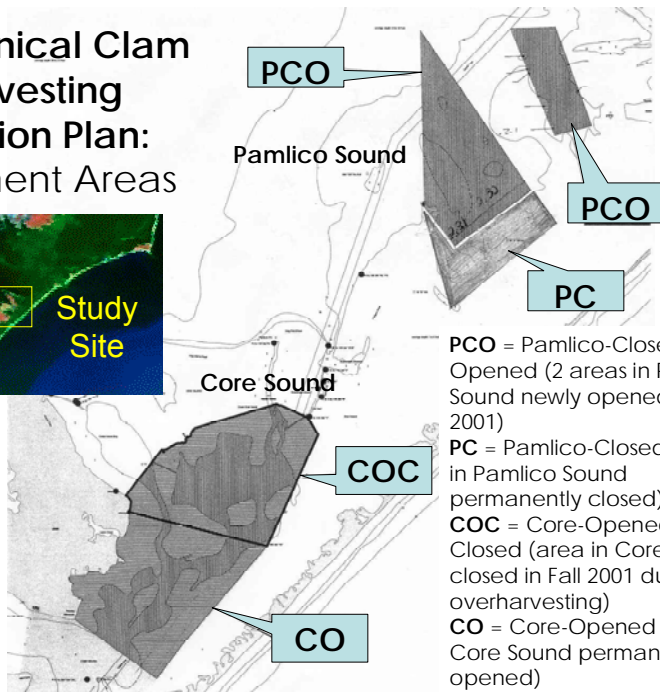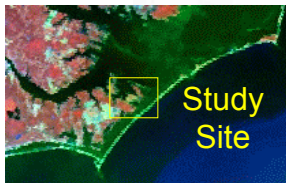
PCO = Pamlico-Closed-Opened (2 areas in Pamlico Sound newly opened in Fall 2001)
PC = Pamlico-Closed (area in Pamlico Sound permanently closed)
COC = Core-Opened-Closed (area in Core Sound closed in Fall 2001 due to overharvesting)
CO = Core-Opened (area in Core Sound permanently opened)

Figure 2.5. Timeline of sampling for the study.
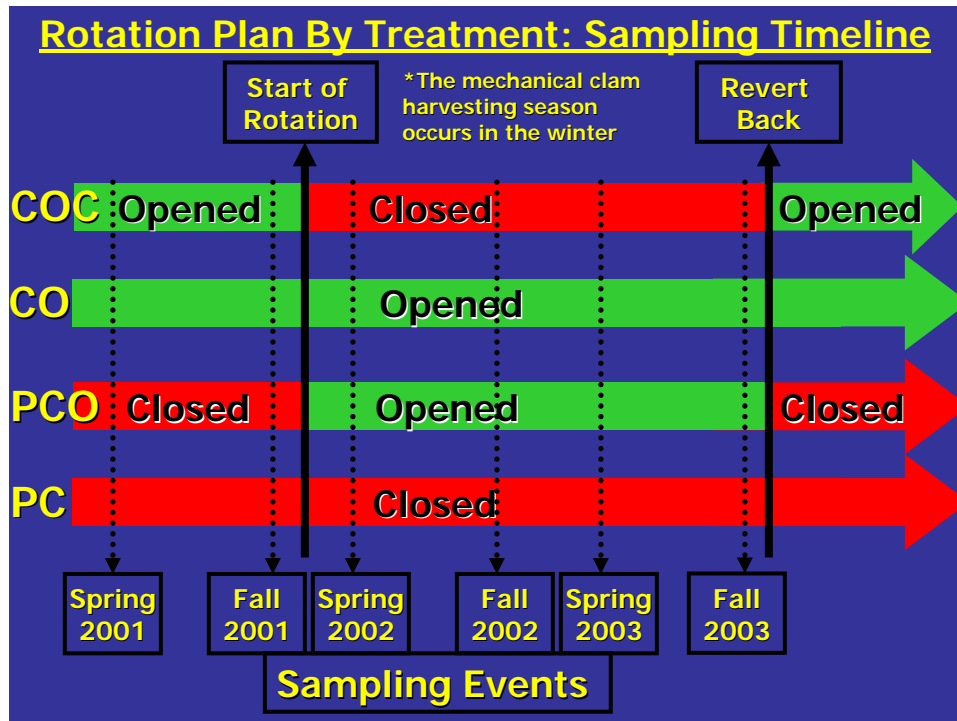
Table 2.1. In Core Sound, the number and ordinal scoring of trawls with *Z. marina* in spring 2001, 2002 and 2003 samples. The locations are CO=Core-Opened and COC=Core-Opened-Closed. The ordinal scores are: A=absent, L=low, M=moderate, and H=high.

Score	CO			COC		
	2001	2002	2003	2001	2002	2003
A	9	8	5	4	3	1
L	3	1	0	5	2	1
M	1	3	7	6	4	6
H	1	0	0	2	3	8
Total	14	12	12	17	12	16

Table 2.2. In Core Sound, the spring 2001, 2002 and 2003 samples of *Z. marina* are dichotomized into high (H) and low (L) counts. In this case, low equals A+L+M. The locations are CO=Core-Opened and COC=Core-Opened-Closed.

Score	CO			COC		
	2001	2002	2003	2001	2002	2003
L	13	12	12	15	9	8
H	1	0	0	2	3	8
Total	14	12	12	17	12	16

Figure 2.6. For the spring (*Z. marina*) samples in Core Sound, Clopper-Pearson Mid-P confidence intervals depicting the proportion of trawls with scores of high as a function of time. A positive and significant effect score indicates that by 2003, CO and COC have become significantly different from each other and that there was an increase in the proportion of trawls with high density seagrass in COC versus CO.
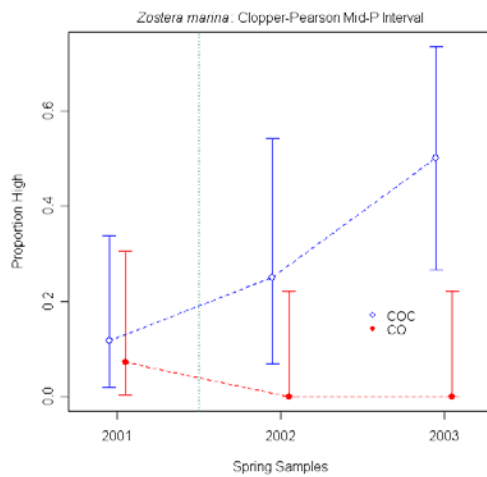
Table 2.3. In Core Sound, the number and ordinal scoring of trawls with *H. wrightii* in fall 2001, 2002 and 2003 samples. The locations are CO=Core-Opened and COC=Core-Opened-Closed. The ordinal scores are: A=absent, L=low, M=moderate, and H=high.

Score	CO			COC		
	2001	2002	2003	2001	2002	2003
A	8	18	5	6	10	8
L	0	2	1	1	0	8
M	1	0	3	3	1	7
H	3	0	4	2	3	8
Total	12	20	13	12	14	31

Figure 2.7. For the fall (*H. wrightii*) samples in Core Sound, Clopper-Pearson Mid-P confidence intervals depicting the proportion of trawls with scores of high as a function of time. There was no significant difference in the proportion of trawls with high density seagrass in COC versus CO from 2001 to 2003.
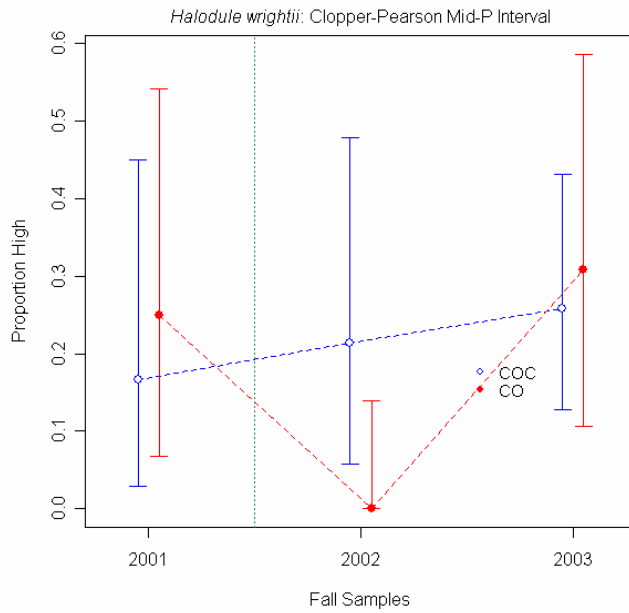
Table 2.4. In Pamlico Sound, the number and ordinal scoring of trawls with *Z. marina* in spring 2001, 2002 and 2003 samples. The locations are PC=Pamlico-Closed and PCO=Pamlico-Closed-Opened. The ordinal scores are: A=absent, L=low, M=moderate, and H=high.

Score	PC			PCO		
	2001	2002	2003	2001	2002	2003
A	4	6	3	14	23	11
L	4	6	8	10	0	1
M	3	0	6	2	0	2
H	1	0	2	0	0	1
Total	12	12	19	26	23	15

Figure 2.8. For the spring (*Z. marina*) samples in Pamlico Sound, Clopper-Pearson Mid-P confidence intervals depicting the proportion of trawls with scores of high as a function of time. There was no significant difference in the proportion of trawls with high density seagrass in PCO versus PC from 2001 to 2003.
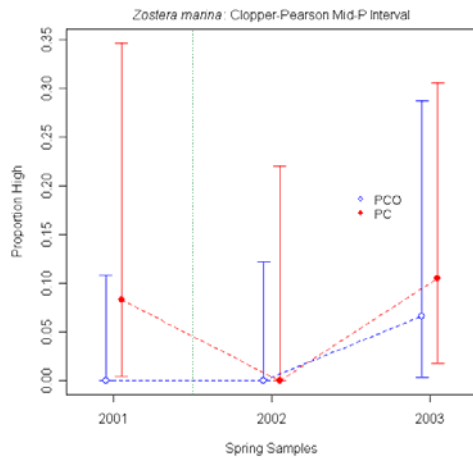
Table 2.5. In Pamlico Sound, the number and ordinal scoring of trawls with *H. wrightii* in fall 2001, 2002 and 2003 samples. The locations are PC=Pamlico Closed and PCO=Pamlico-Closed-Opened. The ordinal scores are: A=absent, L=low, M=moderate, and H=high.

Score	PC			PCO		
	2001	2002	2003	2001	2002	2003
A	11	0	5	17	10	12
L	1	1	3	0	6	1
M	0	6	2	0	5	1
H	0	5	2	0	4	2
Total	12	12	12	17	25	16

Figure 2.9. For the fall (*H. wrightii*) samples in Pamlico Sound, Clopper-Pearson Mid-P confidence intervals depicting the proportion of trawls with scores of high as a function of time. There was no significant difference in the proportion of trawls with high density seagrass in PCO versus PC from 2001 to 2003.
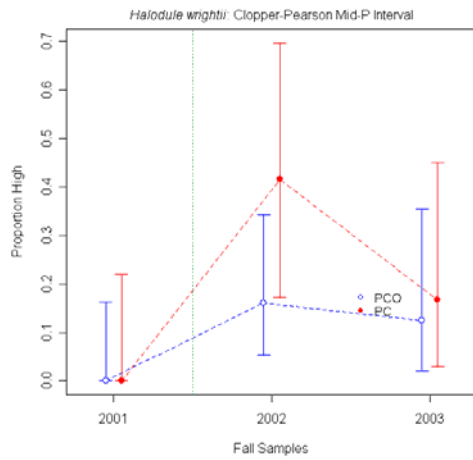
Chapter 2. Appendix.
Effects of Clam Kicking Disturbance on Seagrass Populations in Core and Pamlico Sounds

This appendix contains the series of analyses performed upon the spring Core Sound dataset (*Z. marina*), although the same series was carried out for all treatments during spring and fall. I dichotomize the scores into presence-absence and high-low counts. Additionally, I utilize all four of the categories (A, L, M, H), treating them as either ordinal or assigning each a numerical score.

Dichotomizing the data into presence-absence and high-low counts

First, I dichotomize the spring Core Sound data (*Z. marina*) into presence/absence counts (Table 2A.1). The Clopper-Pearson Mid-P confidence interval is calculated for these data because it is a relatively conservative type of confidence interval (Agresti and Gottard 2005). These intervals are mapped onto a graph of proportion of trawls containing seagrass as a function of time (Figure 2A.1). This graph shows that there is a systematic difference between COC and CO and the magnitude of the difference does not change over time. The formal test of this is to compare the difference between COC and CO in 2003 with the difference in 2001. I use an effect score or point estimate to do this, which I define as:

$$\text{Effect Score} = (p_{COC} - p_{CO})_{2003} - (p_{COC} - p_{CO})_{2001} = \Delta p(2003) - \Delta p(2001)$$

p_{COC} = the proportion of trawls with seagrass in COC at a given sample time p_{CO} = the proportion of trawls with seagrass in CO at a given sample time

$$\Delta p = p_{coc} - p_{co} .$$

For my data I obtain the following:

$$\text{Effect Score} = \left(\frac{15}{16} - \frac{7}{12}\right) - \left(\frac{13}{17} - \frac{5}{14}\right) = -0.0534$$

Since the effect score is negative, there is no evidence for an increase in the presence of seagrass in COC, the protected area of Core Sound. The samples are small and I do not have a standard statistical distribution to apply to this effect score to determine if it is statistically different from zero, so I use 10,000 bootstrap samples to obtain a 95% bootstrap confidence interval of (-0.487, 0.399) for the effect score. Since the interval contains zero, there is no evidence for a change in the relative occurrence of seagrass in trawls between COC and CO over the period of time in which COC was closed using the presence-absence method.

I then divide the data into high-low counts in which low equaled A+L+M (Table 2A.2). The Clopper-Pearson Mid-P confidence intervals are mapped onto a graph containing the proportion of trawls with high seagrass counts as a function of time (Fig 2.6). The effect score is 0.4538. The bootstrap test is significant with a 95% confidence interval of (0.1397, 0.7876). A positive and significant score indicates that there is an increase in the number of high density seagrass counts in COC versus CO during the course of the rotation plan.

Using all the categories and treating them as purely ordinal

Since I have higher quality data than presence-absence and high-low counts

of *Z. marina*, next I utilize all four ordinal categories that I had collected in the field.

The ranking of these categories is: A<L<M<H. To deal with purely ordinal data, an

ordinal-nominal measure of association between COC and CO in each year is

calculated, along with bootstrap confidence intervals. The following equation is used

to calculate the association score, Δ:

$$\Delta_{2003} - \Delta_{2001}, \text{ where } \Delta = P(Y_{COC} > Y_{CO}) - P(Y_{CO} > Y_{COC})$$

The association score indicates if the degree of association between COC

and CO changes over time. Figure 2A.2 displays the estimates of the association

measure for each year along with 95% bootstrap confidence intervals. The

association scores are positive, indicating that samples from COC tend to have more

seagrass in them than the samples from CO at all times. The association scores

also increase over time. The confidence intervals overlap, suggesting that the trend

is not significant. The formal test is the comparison of the distribution of association

scores in 2003 versus the same distribution in 2001 using the bootstrap. Although

the difference in scores indicates a slight increase in seagrass in COC by 2003, the

95% bootstrap confidence interval, based on 10,000 samples, was (-0.284, 0.598).

This interval includes zero, so there is no evidence for a trend in association values

from 2001 to 2003.

Using all the categories and assigning them scores

If it is possible to measure how different two categories are, then treating the categories as purely ordinal loses information. Therefore, I attempt to legitimately assign numerical scores to the different categories of A, L, M, and H for *Z. marina*. Because the original ordinal scale is a subjective assessment of the back side of the cage that is covered in seagrass (the portion of the cage that drags along the estuarine bottom), 0,1,5, and 10 are chosen as numerical scores corresponding to 0%, 10%, 50% and 100% coverage of the cage. Note that because this assignment of the highest category score doesn't account for the possibility that multiple layers of seagrass had built up, 10 might be viewed as the absolute minimum score for the H category. Figure 2A.3 displays the mean scores (with 95% bootstrap confidence intervals) over time for COC and CO using these two scoring systems, as well as a third system that weights the last category more heavily. All three scoring systems suggest that COC and CO are becoming more different over time, so that by 2003 the mean scores in COC and CO are significantly different. The differences for the last two scoring schemes are more pronounced.

In order to carry out a bootstrap test to determine if there is a significant difference over time, I defined an effect score as:

$$\text{Effect score} = \left(\bar{y}_{COC} - \bar{y}_{CO}\right)_{2003} - \left(\bar{y}_{COC} - \bar{y}_{CO}\right)_{2001}$$

The effect score equals a difference of differences in which individual terms are the mean scores for a region at a particular date. Figure 2A.4 shows the 95% bootstrap confidence intervals for this effect score using the three scoring systems

113

displayed in Figure 2A.3. The plot reveals that the results depend on the scoring

system used. The only confidence interval that does not contain a zero is the one

for the third scoring system, and even that one is barely significant. However, the

results suggest another approach that may be useful and is demonstrated in the

main body of the chapter.

Chapter 2 Figures. Appendix.
Effects of Clam Kicking Disturbance on Seagrass Populations in Core and Pamlico Sounds

Table 2A.1. In Core Sound, the spring 2001, 2002 and 2003 samples of *Zostera marina* are dichotomized into presence/absence counts. The locations are CO=Core-Opened and COC=Core-Open-Closed. The scores are A=absent and P=present.

Score	CO			COC		
	2001	2002	2003	2001	2002	2003
A	9	8	5	4	3	1
P	5	4	7	13	9	15
Total	14	12	12	17	12	16

Figure 2A.1. The Clopper-Pearson Mid-P Confidence Interval for the spring samples in Core Sound. There is a systematic difference between the presence of *Z. marina* in COC and CO and the magnitude of the difference does not change over time.
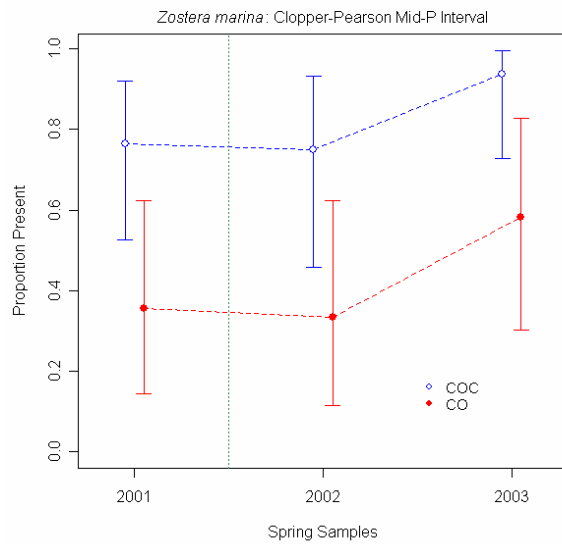
Table 2A.2. In Core Sound, the spring 2001, 2002 and 2003 samples of *Z. marina* are dichotomized into high (H) /low (L) counts. Low equals A+L+M. The locations are CO=Core-Opened and COC=Core-Open-Closed.

Score	CO			COC		
	2001	2002	2003	2001	2002	2003
L	13	12	12	15	9	8
H	1	0	0	2	3	8
Total	14	12	12	17	12	16

Figure 2A.2. The association score between COC and CO for the spring (*Z. marina*) sampling periods. The association scores are positive, indicating that samples from COC tend to have more seagrass in them than the samples from CO, but the trend is not significant.

Core Sound: Pure Ordinal Effect Score Confidence Interval
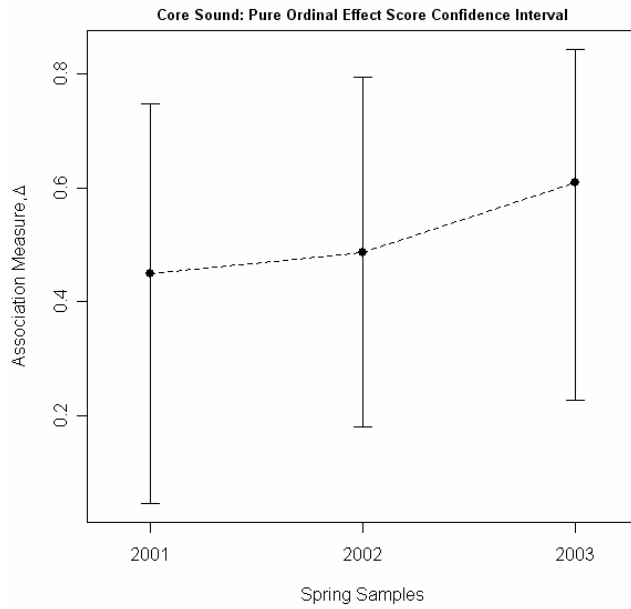
Figure 2A.3. Comparison of effect of category scoring on mean seagrass (*Z. marina*) scores and their confidence intervals. As the upper categories are weighted more heavily, the differences between COC and CO become more pronounced with time. COC and CO are significantly different by 2003 using the third scoring system.
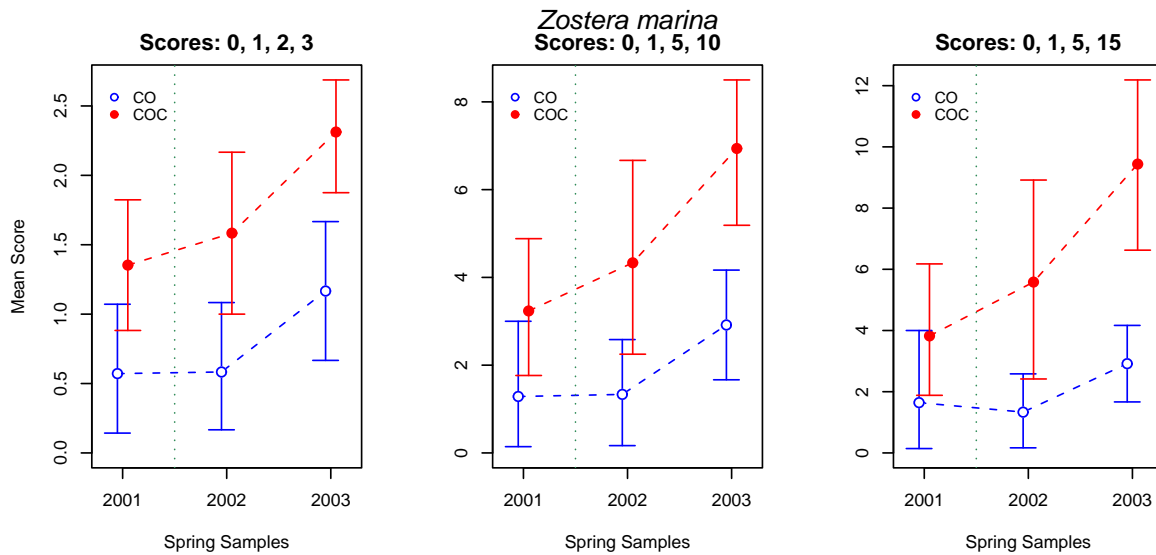
Fig 2A.4. For spring (*Z. marina*) samples from Core Sound, the 95% bootstrap confidence intervals for the effect score using the 3 scoring systems displayed in Figure 2.9.
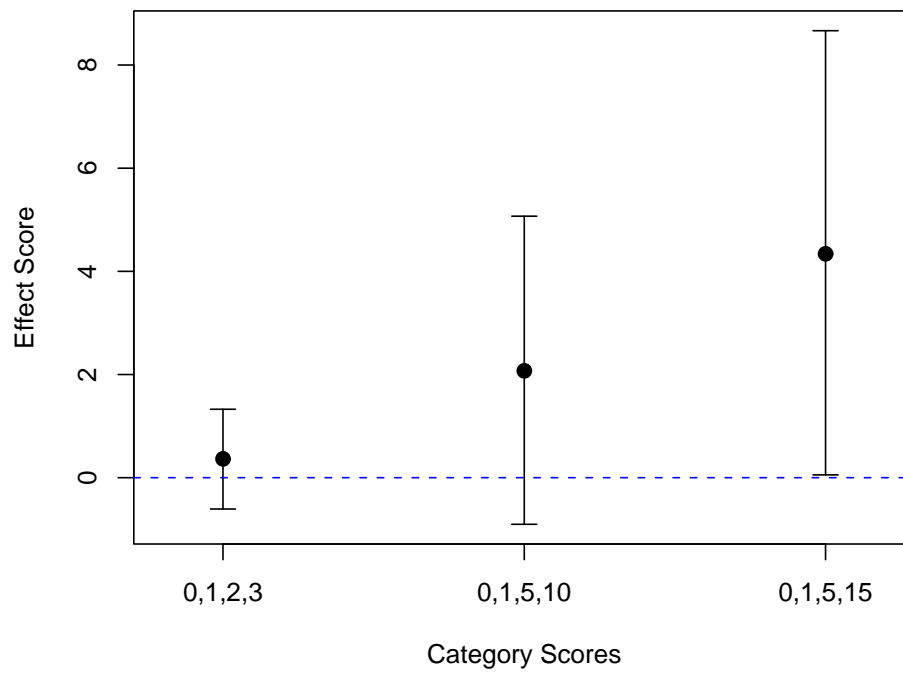
Literature Cited

Agresti A., A. Gottard. 2005. Comment: Randomized confidence intervals and the mid-P approach. Statistical Science **20**:367.

Creed, Joel C., Filho,Gilberto M.Amado. 1999. Disturbance and recovery of the macroflora of a seagrass (Halodule wrightii Ascherson) meadow in the Abrolhos Marine National Park, Brazil: an experimental evaluation of anchor damage. Journal of Experimental Marine Biology and Ecology **235**:285-306.

Duarte C. M. a. C., C.L. 1999. Seagrass biomass and production: a reassessment. Aquatic Botany **65**:159-174.

Fonseca, Mark S., Bell,Susan S. 1998. Influence of physical setting on seagrass landscapes near Beaufort, North Carolina, USA. Marine Ecology Progress Series **171**:109-121.

Fonseca, Mark S., Thayer, Gordon W., Chester,Alexander J. 1984. Impact of scallop harvesting on eelgrass (Zostera marina) meadows: implications for management. North American Journal of Fisheries Management **4**:286-293.

Guthrie, James F., Lewis,Curtis W. 1982. The clam-kicking fishery of North Carolina. Marine Fisheries Review **44**:16-21.

Hemminga, Marten A. and Duarte, Carlos M. 2000. Seagrass Ecology. Cambridge University Press. 298pp.

Irlandi, E. A., Peterson,C.H. 1991. Modification of animal habitat by large plants: mechanisms by which seagrasses influence clam growth. Oecologia **87**:307-318.

Jenkins, G.P., Black, K.P., Wheatley,M.J.and Hatton, D.N. 1997. Temporal and spatial variability in recruitment of a temperate, seagrass-associated fish is largely determined by physical processes in the pre- and post-settlement phases. Marine Ecology Progress Series **148**:23-35.

Orth, R.J., Heck, K.L.,Jr.and van Montfrans, J. 1984. Faunal communities in seagrass beds: a review of the influence of plant structure and prey characteristics on predator-prey relationships. Estuaries **7**:339-350.

Peterson, C. H., Summerson, H. C., Duncan,P.B. 1984. The influence of seagrass cover on population structure and individual growth rate of a suspension-feeding bivalve, Mercenaria mercenaria. Journal of Marine Research **42**:123-138.

Peterson, Charles H., Beal,Brian F. 1989. Bivalve growth and higher order interactions: importance of density, site, and time. Ecology **70**:1390-1404.

Peterson, Charles H., Summerson, Henry C., Fegley,Stephen R. 1987. Ecological consequences of mechanical harvesting of clams. Fishery Bulletin **85**:281-298.

Reusch, T.B.H., Borstrom, C., Stam, W.T.,and Olsen, J.L. 1999. An ancient eelgrass clone in the Baltic. Mar Ecol Prog Ser **183**:301-304.

Short F. T. a. W., S. 1996. Natural and human-induced disturbance of seagrasses. Environmental Conservation **23**:17-27.

Stephan, C. Dianne, Peuser, Robin L., Fonseca,Mark S. 2000. Evaluating fishing gear impacts to submerged aquatic vegetation and determining mitigation strategies. ASMFC Habitat Management Series **5**:

Thayer, G.W., Fonseca, M.S.,and Kenworthy, W.J. 1997. Ecological value of seagrasses: a brief summary for the ASMFC Habitat Committee's SAV Subcommittee. ASMFC Habitat Management Series **1**:5-10.

Walker R. L. 1989. Exploited and unexploited hard clam, Mercenaria mercenaria (L.) populations in coastal Georgia. Contributions in Marine Science **31**:61-75.

Chapter 3.
Changes in Size Distribution of Hard Clam (*Mercenaria mercenaria*) Populations in Core and Pamlico Sounds as a Result of Rotating MPAs.

INTRODUCTION

Previous studies have determined that harvesting alters the age and size distribution of hard clam (*Mercenaria mercenaria*) populations because of the selective removal of certain size classes of adult clams. For instance, overharvesting of hard clams in central NC has led to recruitment overfishing, in which recruitment was severely reduced by the removal of adult spawners from clam populations (Peterson 2002). Clam populations in 3 different habitats (muddy sand creek, sand flat and seagrass bed) were sampled 11 times from 1978 to 2001. During this time period, there was a reduction in recruitment of 65 to 72% compared to original levels which was related to a 5-fold increase in landings. Eventually, landings diminished as well, dropping 50% from 1983 to 2000. From 1980 to 1997, there were decreases of 17 to 95% in population densities and 24 to 83% in spawning stock biomass.

The results of an earlier study targeting a hard clam population in a tidal creek in Core Sound, NC, suggested that extended and intense commercial clamming shifted the population towards younger age classes (Peterson *et al.* 1983). Additionally, low recruitment was consistent with a 4-fold increase in commercial

harvesting, indicating that the spawner population in central NC already may have begun to decline by that time period.

In a study in Narragansett Bay, the *M. mercenaria* populations of three areas with different management schemes were sampled (Rice *et al.* 1989). The first was closed since the 1930's, the second was heavily fished since the 1930's, and the third was closed for 2 decades. The average clam lengths in the three areas were 62mm, 31 mm, and 61 mm, respectively. Additionally, there were significantly more juveniles in the second (heavily fished area) than in the other two areas. In the fished area, the oldest clams were 12 years old, whereas in the closed areas, the oldest clams were 25 years old. The population density of the first area was approximately 2.5 times that of the second and 4 times that of the third, suggesting that increased protection led to higher densities. The authors concluded that harvesting removes adults and increases abundances of juveniles, speculating that the mechanisms behind this were the reduction of the populations of competing adults or sediment disturbance.

Malinowski (1985) also found that clam densities increased over time in unharvested populations. In Georgia, Walker (1989) concluded that light or heavy fishing pressure decreased the ranges of clam sizes and ages. The number and size of clam aggregations are decreased by harvesting (Fegley 2001).

In this study, I assess the effects of the rotation plan on the size structures and age-size relationships of the clam populations in Core and Pamlico Sounds.

METHODS

Experimental Design

The four treatment areas of the study are mapped in Figure 3.1:

1. **Core-Opened-Closed (COC),** the area in Core Sound that was closed in fall 2001 for two years.

2. **Core-Opened (CO),** the area in Core Sound that remained opened.

3. **Pamlico-Closed-Opened (PCO),** the bottom newly opened in fall 2001 for two years (separated into two portions due to the presence of a large seagrass bed).

4. **Pamlico-Closed (PC),** the only area in southeastern Pamlico Sound that is permanently closed yet also accessible by both clam kicking boat and gear.

I sampled for clams available to the fishery during six different time periods: both spring and fall in 2001, 2002 and 2003. To sample for clams and associated data, I used the clam kicking method practiced by local fishermen (clammers in this area are all male). For the first five sampling periods, I utilized the services and boat of Mr. Dallas Goodwin, who owned a 38-foot shrimp trawler outfitted with clam kicking gear. Unfortunately, his boat was destroyed by Hurricane Isabel in September 2003, so I collected data with another clammer who owned a comparable kicking boat.

I directed the fishery-independent sampling and originally developed a random sampling scheme using ArcView GIS. However, the study areas have many shoals, crabpots, impoundment nets and discarded pieces of fishing gear which restricted my sampling, resulting in a haphazard sampling scheme. During the six

sampling periods I covered each of the four treatment areas as extensively as possible, resulting in a minimum of twelve trawls per treatment area. I counted the number of legal clams (width equal to or greater than one inch or 25.4 mm) caught in each five-minute trawl. I was able to collect relatively few larger sublegal clams, as the gear is designed to exclude sublegal clams less than approximately 0.75 in or 19 mm in width. I retained a minimum of 200 clams total per treatment area for further laboratory analyses including size and age data.

For this section of the study, I retained a randomized subsample of approximately 200 clams from the catches of each of the four treatment areas and six sampling periods for further analysis of size and age in the laboratory. For the first sampling period in spring 2001, I measured length, height, and width of each clam with digital calipers. I dried the soft tissue to constant weight (approximately 3 days) in a 65°C drying oven to obtain dry tissue mass and cut and aged each clam to within 0.5 years using Peterson's methods (Peterson *et al.* 1983). For the subsequent sampling periods, I measured length, height, and width of each of the 200 clams retained for each subsample.

For both Core and Pamlico Sounds, I performed analyses on the size distribution of the clam populations. Although details are given in the analysis section, I calculated the mean, standard deviation (SD), median, interquartile range (IQR) and median absolute deviation (MAD) for clam widths for the subsamples of clams from all six sampling periods. I performed simulation experiments which I have summarized in the analysis section. Additional details on the Pamlico Sound simulation are included in Appendix 3.

ANALYSIS AND RESULTS

Part 1. Size Distribution of the Clam Populations in Core Sound
Tracking size distributions over time using univariate statistics

Figures 3.2 and 3.3 depict the sampled distributions of clam width over the

course of the study for COC and CO, respectively. Although width was used as the

size measurement, there were similar results for length and height. While the

distributions in CO and COC appeared to become more different over time, it was

difficult to quantify this difference based on Figs. 3.2 and 3.3 alone. To summarize

the distributions, selected univariate statistics were tracked over time.

The sample mean and standard deviation (SD) were easily upset by the

presence of even a single outlier and were sub-optimal for non-normal distributions.

Standard measures of location and variability such as the mean and SD were

probably inadequate for the distributions in Figure 3.2 and 3.3. Therefore, in addition

to the mean and SD, I considered 3 robust alternatives: the median for location and

the interquartile range (IQR) and median absolute deviation (MAD) for variability.

Figure 3.4 displays the trends for the two measures of location (mean and median)

for COC and CO, while Figure 3.5 displays the trends for the three different

measures of variability (SD, IQR and MAD).

Neither plot in Figure 3.4 showed any obvious time-related differences

between COC and CO. Both graphs have similar trajectories. While the mean width

for clams in COC was consistently less than the mean width of clams in CO, the

median, a more robust measure, failed to find a consistent difference between them

(the two trajectories crossed repeatedly and their confidence intervals completely overlapped).

The measures of variability have different implications. All three variability statistics indicated that shell width was typically less variable in COC than it is in CO. The SD plot (Figure 3.5a) suggested that shell width in COC was always significantly less variable than in CO. The pattern shown for IQR (Figure 3.5b) was consistent with the SD results although there was some indication that the difference in IQR was increasing over time. This increase began before the rotation plan was implemented. The MAD plot (Figure 3.5c) was very different. The MAD trajectories were almost perfectly parallel in both areas until a year after the rotation plan was implemented, after which the trajectories diverged so that MAD in CO increased while MAD in COC decreased.

The MAD trajectories for length and height tell were even more striking (Figure 3.6). Here the trajectories were initially parallel until six months after implementation of the rotation plan, after which they diverged. This divergence occurred one sample period before the start of the divergence for width (Figure 3.5c).

The statistics displayed in Figs. 3.5 and 3.6 were calculated as follows.

$$SD = \sqrt{\frac{\sum_{i-1}^{n}(x_i - \bar{x})^2}{n-1}}$$, (1)

$$IQR = x_{[0.75n]} - x_{[0.25n]}$$, and (2)

128

$$\text{MAD} = \frac{1}{0.6745} \underset{i}{\text{median}} \left\{ \left| x_i - \underset{j}{\text{median}}(x_j) \right| \right\}$$

where n was the sample size. In the formula for the IQR $x_{[i]}$ denoted the ith order statistic so that IQR was calculated as the difference in the sample quartiles. For a normal population it was the case that $\text{MAD} \approx 0.6745 \times \text{SD}$. The multiplier in the formula for MAD adjusted the estimate so that it was of a comparable magnitude to SD for a normal population.

The three measures of variability in Figure 3.5 depicted contradictory results. Given the non-normal nature of the distributions shown in Figs. 3.2 and 3.3, it was not surprising that MAD and SD showed different patterns. The fact that the IQR, also a robust measure of variability, more closely resembled SD rather than MAD was unexpected.

There were two important questions:

1. Did the variability in clam size increase in CO and decrease in COC following implementation of the rotation plan? If this was true, then the MAD results were acceptable and the IQR and SD should be dismissed.

2. If a divergence in variability can be supported, what were the resulting management implications?

In the next section, a mechanistic model was developed to address these questions.

A Probabilistic Model of Clam Harvesting

Regulations prohibit the harvesting of small clams (width less than 1 inch or 25 mm) and large clams or chowders usually are not as valuable as smaller clams. Therefore, if fishermen catch more clams than the daily bag limits allow, they should prefer clams of an intermediate size and toss back larger clams; however, if they do not catch more than the limit, they will keep the larger clams. In practice smaller-sized (<25.4mm in width) clams pass through the clam kicking gear or are tossed back since they are against regulations and larger clams should be tossed back based on their lower market value according to the restriction described above. Further analysis of trip ticket data may help to elucidate this issue of which clams are kept and which are tossed back depending on whether or not the bag limit is reached. To simulate this situation, a probabilistic experiment was run. Clams that were randomly chosen from a specified size distribution were then accepted (remain in the population) or rejected according to the following rules.

1. If the clam width < 25 mm, accept it.
2. If the clam width > 50 mm, accept it.
3. If the clam width is between 25 and 50 mm, accept it with probability $1 - p$, where $0 < p < 1$. Here p can be viewed as a proxy for harvesting intensity.

These rules define a probabilistic model for the clam population that was not harvested, i.e., the clam population that remained at the end of the kicking season. By varying p, the effect that fishing intensity had on the size distribution of the unharvested population can be studied.

Figure 3.7 illustrated the model for a population in which clam width was normally distributed, with mean = 36 mm and SD = 12 mm. These choices for the parameter values match the sample statistics for Core Sound that were obtained at the beginning of the study (Figs. 3.2 and 3.3). A normal distribution was chosen for convenience for the first attempt to understand the relationship between fishing intensity and clam size variability.

The experiment illustrated in Figure 3.7 was carried out at varying levels of fishing intensity (variable p) until a total of 500 clams were retained at each run. The MAD statistic was then calculated for the sample. The experiment was repeated 100 times and 95% Monte Carlo-based confidence bounds on MAD were obtained. Figure 3A.5 showed the results. As fishing pressure increased, the variability of the remaining clam population (as measured by the increase in MAD) also increased.

Figure 3.8 demonstrated that the divergence in the MAD trajectories observed in Figure 3.5c after the rotation plan began could result from changes in fishing pressure in COC versus CO. The increased fishing pressure on the clams in CO could have led to the observed increase in size variability, while the decreased fishing pressure on the clams in COC could have led to the observed decrease in size variability.

Because there were different conclusions obtained with the other variability statistics SD and IQR, the simulation experiment was rerun with all three variability estimates. Figure 3.9 showed the results. MAD was far more sensitive to the effect of fishing pressure than was SD. IQR was far more sensitive than was MAD. This was inconsistent with Figure 3.5 where SD and IQR more closely resembled each

other. Therefore, if the fishing pressure hypothesis correctly explained the MAD

results in Core Sound, the simulation experiment was missing a crucial ingredient.

Because the original experiment was run with a normal distribution, this was

not an accurate representation because the distribution of clam width was not

normal. To capture the bimodal pattern visible in a number of the distributions

shown in Figs. 3.2 and 3.3, a distribution that was a mixture of normal distributions

was constructed. Figure 3.10a shows an equal part mixture of two normal

distributions, one with mean $\mu = 55$ and $\sigma = 13$, the other with mean $\mu = 25$ and $\sigma = 4$. The mixture distribution obtained resembled the observed distribution for CO in

spring 2002.

The algorithm described in Figure 3.7 was then applied to this distribution. As

an example, Figure 3.10b showed the distribution after the simulated clam

population was subjected to a 50% fishing intensity rate. Samples of size 500 were

taken from bimodal distributions subjected to different levels of fishing and the

variability estimates SD, IQR, and MAD were obtained as in Figure 3.9. Figure 3.11

showed the results. Unlike Figure 3.9 where IQR showed the largest rate of change

with varying fishing intensity, in Figure 3.11 MAD showed the greatest rate of

change, while IQR and SD were barely distinguishable. This was consistent with the

data actually obtained from Core Sound as shown in Figs. 3.2 and 3.3.

By changing the parameters of the simulation it was very easy to make either

IQR or MAD more sensitive to changes in fishing pressure, although in most

scenarios they exhibited similar behavior. However, SD varied only slightly as a

function of a changing harvest rate.

Part 2. Size Distribution of the Clam Populations in Pamlico Sound
Tracking size distributions over time using univariate statistics

Figs. 3.12 and 3.13 showed the sampled distribution of clam width for the two Pamlico samples. The distributions were quite different from Core. The variability was less and there was only slight bimodality, relative to the bimodality that manifested itself repeatedly in Figure 3.2 and 3.3. Figs. 3.14 and 3.15 summarized changes over time in these distributions by examining the same five summary statistics used in the study of Core Sound.

There was a high degree of oscillation in all of the displayed statistics. Unlike Core Sound, all five statistics showed a consistent pattern of oscillations that were greater for PCO and got larger once the rotation plan begins. Interestingly the oscillations of the location statistics were out of phase with the oscillations of the variability statistics. When the mean or median were high, the variability (as measured by SD, IQR, or MAD) was at a low. On the other hand, when the mean and median were lowest the variability was at a maximum. Since these populations were different from those in Core Sound, a different analysis was applied to the Pamlico Sound dataset.

The Effect of Fishing on Clam Height

By spring 2003 the height distribution of clams in PC and PCO was markedly different (Figure 3.16). Examination of histograms of the height distributions suggested that a mixture of normal distributions would an adequate fit. This mixture of distributions was parameterized as follows.

$$f\left(p,\mu_1,\sigma_1^2,\mu_2,\sigma_2^2\right)= pN\left(\mu_1,\sigma_1^2\right)+(1-p)N\left(\mu_2,\sigma_2^2\right) \tag{1}$$

This probability distribution was fit to the data for PC and PCO separately using maximum likelihood estimation. The fitted and empirical distributions are shown in Figure 3.17. Notice how close the estimated mixture model came to the nonparametric density estimate (Appendix 3). Model fit was checked in two ways, using the parametric Pearson chi-square test and a randomization test. There was no evidence for rejecting the fit of the mixture models to either PC or PCO from either test (Appendix 3).

The two models were compared by asking the parallel questions: Did the mixture model for PC fit the data for PCO and did the mixture model for PCO fit the data for PC? The individual mixture models fit their own data quite well, but each was completely inadequate as a model for the other area's data (Appendix 3).

Modeling the Effect of Fishing

Based upon the results of the previous section, it was reasonable to use a mixture model as a surrogate for the actual distribution of heights in PC and PCO. This had some immediate advantages, because I used the mixture distributions to generate observations that were used in simulation experiments (such as the simulation experiment applied to widths in Core Sound). In particular I observed the effect of simulated fishing on the distribution of height in the simulated population.

Spring 2003 was the first time that the size distributions in PC and PCO looked very different from each other. Since one area was protected and the other area was opened, the observed differences in size distribution may be attributed to fishing. For this experiment, I assumed that if PCO were closed to fishing, its size distribution in spring 2003 would be roughly the same as the distribution observed in PC. Using the simulated data for PC in spring 2003, fishing pressure was applied to see if the resulting distribution was made to resemble what was actually obtained for PCO.

The three parameters that were controlled were the fraction of the population that can be removed by fishing and the upper and lower limits of the size range of clams that were treated as "catchable". Legal limits and market constraints were defined in terms of clam width rather than height, so it was useful to define these parameters in terms of width (Appendix 3). Using the simulated data for PC in spring 2003, I selected upper (u) and lower (l) bounds on width (which was converted to bounds on height using the regression equation) and a fishing fraction, f, and removed that fraction of the "catchable" clams from the simulated population. Then I compared the distribution that results to the actual distribution in PCO. Formal goodness of fit tests were applied.

Figure 3.18 shows the result for various choices of u, l, and f. In each plot, the red and blue curves were the density estimates for data simulated using the fitted mixture models for PC (red) and PCO (blue). The green curve was the density estimate for the data that resulted from applying fishing pressure to PC. The histogram displayed was for the clams that were harvested (corresponding to the

green curve). Appendix 3 contains a few more examples of what the model looked like when the parameters were changed.

DISCUSSION

Part 1. Size Structure of the Clam Populations in Core Sound

Examining the size distributions over time, the COC and CO trajectories for measures of central tendency, mean and median, and for most measures of variability, SD and IQR, were almost parallel to each other. Curiously, one measure of variability, MAD, stood out as an exception to this pattern. The MAD trajectories, while initially parallel, became wildly divergent once the rotation plan is implemented. It is tempting to ascribe this change to the rotation plan; however, the absence of an effect on the other statistics must be explained.   Although it may appear to be obvious that fishing out the middle should lead to an increase in size variability, that's not exactly what is seen in these statistics. To understand the conflicting signals that were obtained, a simulation experiment was carried out to see if the observed pattern could be reproduced: no change in the median or mean, no or minimal change in the SD and IQR, but a large change in MAD. Parameters manipulated in the simulation were the initial size distribution of the population, the range of sizes fished, and the intensity of the fishing pressure.

Starting with a normally distributed size distribution and variable fishing pressure, there was no change in median or mean, but all three dispersion measures increased as fishing pressure was increased. Changing the range of sizes of clams that were fished had no effect on this pattern. Starting with a bimodal

size distribution and variable fishing pressure, there was no change in median or mean as fishing pressure increased, similar to the first run. The effects on the dispersion measures were mixed and were highly dependent on the size ranges that were fished. For most choices all three variability measures increased as fishing pressure was increased. But for certain fishing size ranges, increasing fishing pressure had only a minimal impact on the SD and IQR, but a large and dramatic effect on MAD.

There was a synergy between an initial bimodal size distribution and the intensified fishing pressure that is picked up by MAD but not the others. Because the initial bimodal size distribution is probably a consequence of a long history of "fishing out the middle", what was seen is some kind of positive feedback on the MAD statistic due to selective intensified fishing pressure.

There are two major implications of this analysis. The first is that the connection between a specific variation measure, MAD, and fishing pressure is an interesting result. It apparently arises because of this particular combination of a bimodal size distribution and a fishing behavior where the middle size classes are harvested. The result becomes more interesting when it is realized that the bimodal size distribution is probably also a product of fishing pressure. This leads to the speculation that when clammers fish out the middle of a population in which the middle has been previously fished out, MAD will be most sensitive at detecting this. Although the hard clam fishery is unusual in that the middle size classes are the most valuable instead of the larger ones, these results may be applicable to fisheries

137

in which there are slot limits and the middle sizes are the ones that are legally harvested (in order to protect the larger, older fish).

The second is that the simulation result is not just a restatement of the obvious observation that fishing out the middle increases variability. First the story is far more complex as has been outlined above. More importantly is that having linked increases in MAD to increases in fishing intensity, an indicator of the effect the rotation plan had on Core Sound has been obtained. Both areas were fished initially and it can be assumed that the fishing pressure was roughly the same (as indicated by the parallel trajectories for many of the statistics). Once the rotation plan began, MAD in COC decreased. This corresponds to what actually was known to have happened because fishing pressure was eliminated as a result of the closure. Being able to detect a change in the clam population by sampling that can be linked back to a management strategy provides support that the random sampling was an accurate portrayal of the population as a whole. With a study area as large as this one (4500 acres), this indicates that the sample actually was random. The more interesting result is that MAD in CO increased. If clammers were fishing in Pamlico Sound instead, CO would have continued on its pre-rotation MAD trajectory. Instead, MAD dramatically increased. Therefore, one of the effects of closing one half of Core to clamming (COC) was to intensify the fishing pressure on the remaining half of Core (CO). This is obviously an undesired consequence and confirmed by the trip ticket data. In the year before the rotation plan, there were 892 trips to Core Sound (COC and CO). Dividing the trips from the prior year in half (which is the best that can be done with these data), there were 446 trips to CO. In

the first year, there were 562 trips to Core Sound (CO only) and 200 Pamlico. In the second year, there were 693 trips to CO and 48 to Pamlico. The number of trips to CO increased from 446 to 562 to 693 over the 3 years of the study.

Part 2. Size Structure of the Clam Populations in Pamlico Sound

Pamlico Sound shows a dramatically different pattern from Core Sound. In Pamlico both areas exhibit an oscillatory pattern in measures of central tendency (mean and median) and in measures of dispersion (SD, IQR, and MAD) such that the peaks of these two sets of measures are out of phase with each other. Dispersion patterns achieve their maximum in fall and their minimum in spring. For the measures of central tendency the pattern is reversed. What is apparent from the trajectory plots is that once the rotation plan begins, the oscillations in PCO become more extreme, with larger amplitudes, giving the impression of wildly divergent oscillations.

The overall oscillatory pattern in Pamlico can be explained. Examination of size distributions reveals that typically there is a small influx of small-sized clams in the fall. The overall distribution of clam sizes in Pamlico is well-approximated by a mixture of two normal distributions that differ primarily in their means (Figure 3.17). The normal distribution with the larger mean comprises about 80% of the population. By spring the smaller "population" more or less disappears and appears to be absorbed into the larger population. The smaller population that "appears" periodically may be a consequence of episodic recruitment, timed so that by fall a new cohort has achieved a size large enough to be trapped by the kicking gear.

The influx of these small clams in fall leads to a decrease in mean size and an increase in variability. By spring, through growth and attrition these smaller individuals are absorbed into the main population and with no further recruits the overall population mean increases and the variability decreases. This is exactly what the data show in both parts of Pamlico.

Why does this pattern get exaggerated in the area of Pamlico that was opened to fishing? A population model for the clams in Pamlico was developed to answer this question. Age-size measurements taken in spring 2001 were used to develop a model of the age-size relationships in these clams. Based on the normal mixture models fit to the fall 2001 data, the magnitude of episodic recruitment was estimated. The goal then was to use these estimates to project the initial spring 2001 population forward in time. Once a satisfying fit to observed size distributions was obtained the next step would be to add fishing pressure and see if the divergent oscillations observed in the field could be reproduced as a function of fishing pressure alone.

Although the projections provided a reasonable fit to the data, there were too many speculative features to this model to pursue it further. In particular, because of the constraints of the age-size relationship used in the population projections, it was not possible to reproduce the out-of-phase oscillations in mean and variance measures (Figure not shown).

A different approach was used. If PC and PCO can be viewed as replicates of each other so that the only thing that distinguishes them is that one is opened to fishing and the other is not, it should be possible to start with a model for the

population of PC and by adding only fishing pressure convert it into a model for the population of PCO. Focusing on spring 2003 and using separate simple normal mixture models, adequate fits to the size distributions were obtained separately for PC and PCO. Neither of these models provided an adequate fit for the other population, confirming that the populations were different at this time. Graphically the populations look very different from each other at this time period.

Simply by applying fishing pressure and adjusting the size limits used to determine what clams were removed, it was possible to move the PC distribution in the direction of the PCO distribution. Whereas it was never possible to do this in a way to adequately fit the data statistically (as measured by Pearson goodness of fit tests), it was clear both graphically and analytically that the fit was improved dramatically. This failure helps make the case that PC and PCO are not replicates of each other but differ in important ways.

There are 3 conclusions of this analysis. The first is that population size structure in Pamlico shows natural oscillations. The analysis suggests that this is a result of episodic recruitment, such that new size cohorts appear in the population periodically but with gaps during which there is no new recruitment. The second is that the effect of fishing pressure is to dramatically increase the amplitude of these oscillations. The third is that simulation experiments suggest that the size distribution in PC can be largely turned into the size distribution of PCO simply by adding fishing pressure. Differences still remain suggesting that PC and PCO differ from each other systematically.

Chapter 3 Figures.
Changes in Age and Size Structure of Hard Clam (*Mercenaria mercenaria*) Populations in Core and Pamlico Sounds as a Result of Rotating MPAs

Figure 3.1. Map of the study area in Carteret County, NC, with marked treatment areas.

Mechanical Clam Harvesting Rotation Plan: Treatment Areas

PCO

Pamlico Sound

PCO

PC

Study Site

Core Sound

COC

CO

PCO = Pamlico-Closed-Opened (2 areas in Pamlico Sound newly opened in Fall 2001)
PC = Pamlico-Closed (area in Pamlico Sound permanently closed)
COC = Core-Opened-Closed (area in Core Sound closed in Fall 2001 due to overharvesting)
CO = Core-Opened (area in Core Sound permanently opened)
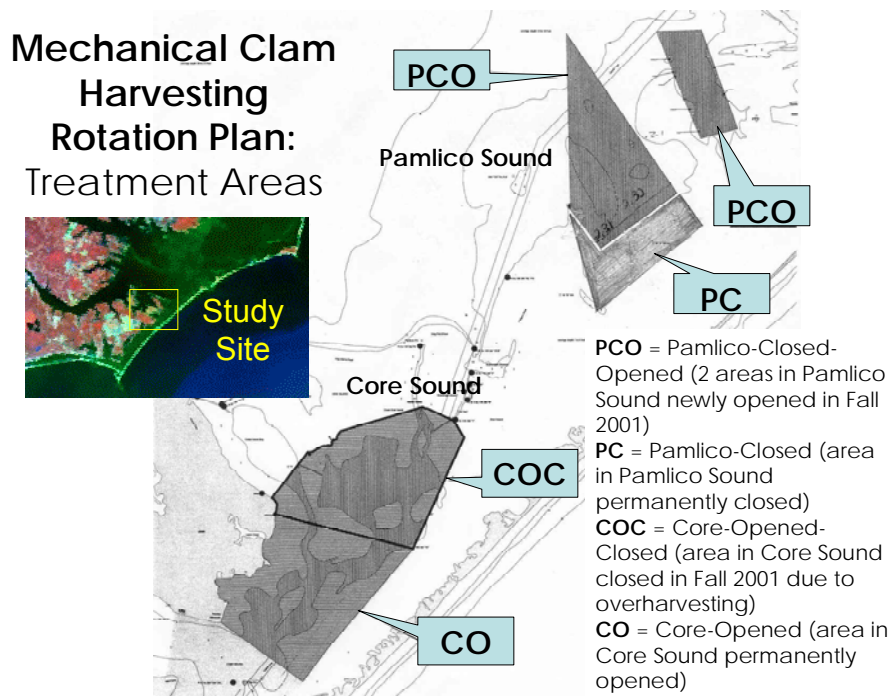
Figure 3.2. Histogram of the distribution of clam width in COC over the course of the study. Note that the distributions often display bimodality.

Distribution of Width for COC
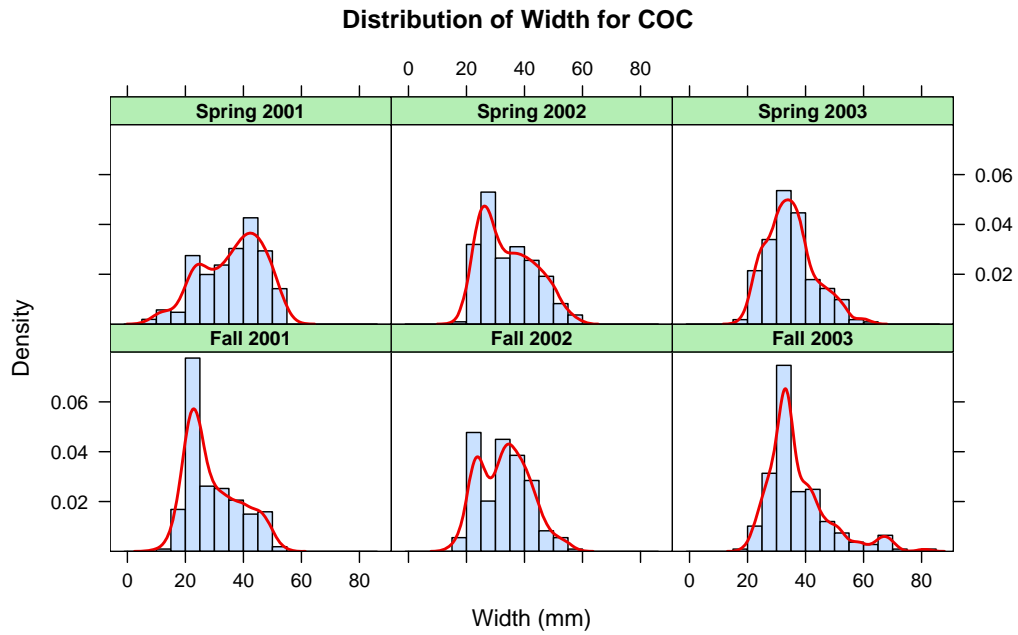
Figure 3.3. Histogram of the distribution of clam width in CO over the course of the study. Note that the distributions often display bimodality.

Distribution of Width for CO
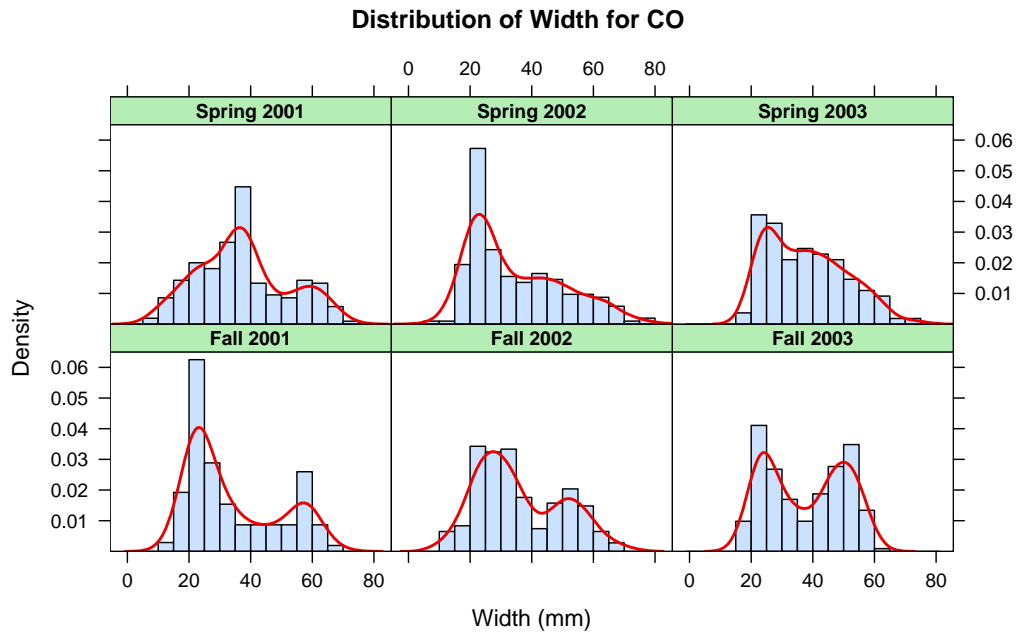
Figure 3.4. Trends in location over time for areas in Core Sound based on (a) the mean, and (b) the median, a robust alternative. Confidence intervals are based on 999 bootstrap replicates from the empirical distribution.

(a)

(b)
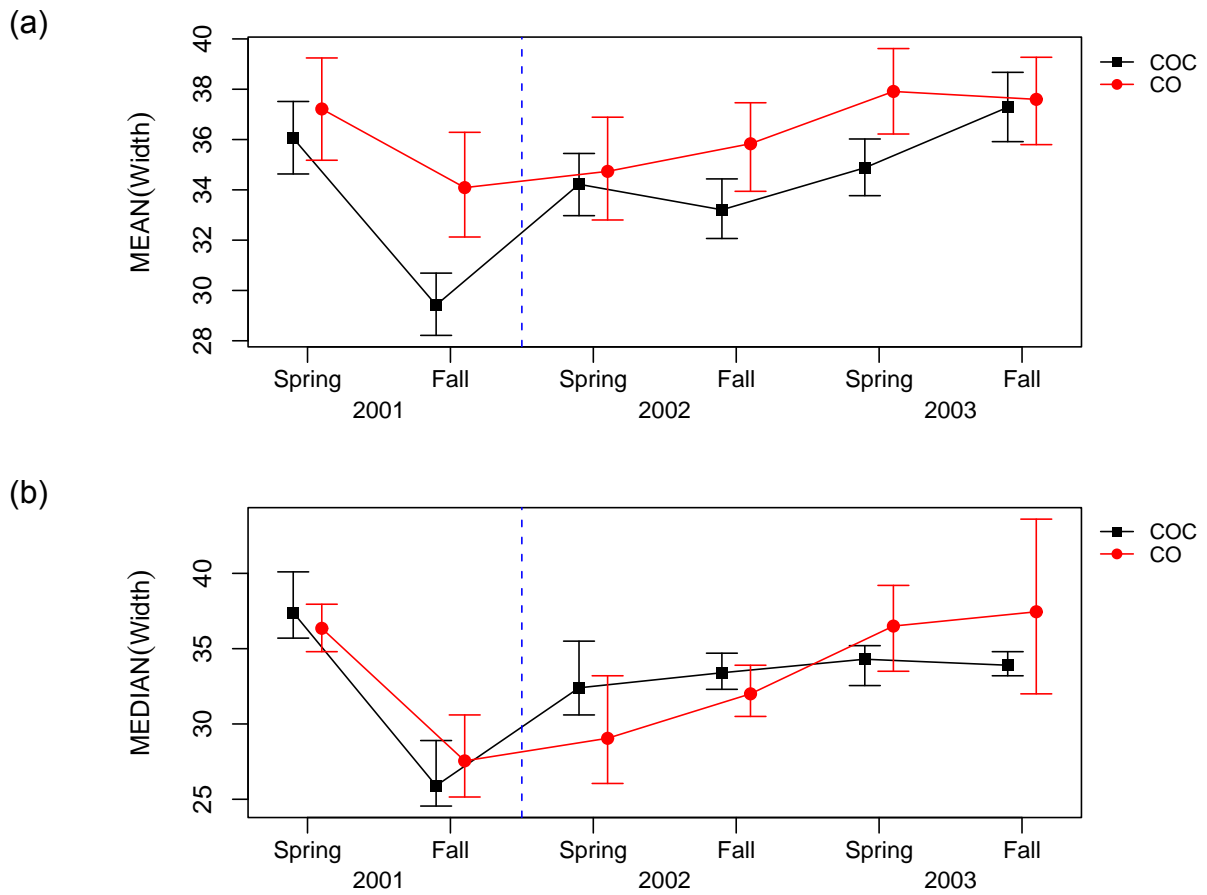
Figure 3.5. Trends in scale over time for COC and CO based on (a) the standard deviation (SD), and two robust alternatives, (b) the interquartile range (IQR) and (c) the median absolute deviation (MAD). The displayed confidence intervals are based on 999 bootstrap replicates from the empirical distribution.
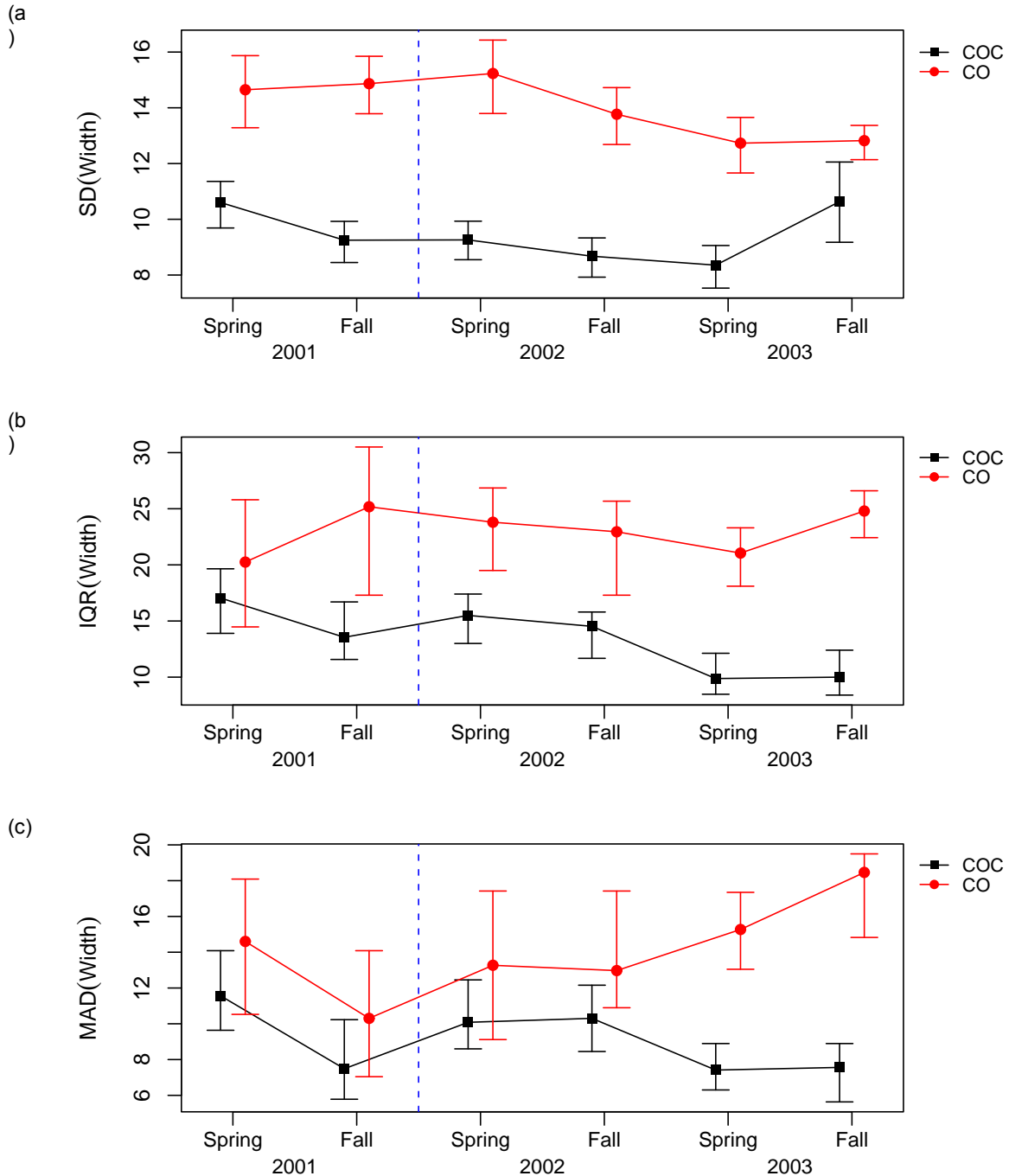
Figure 3.6. Trends in MAD, median absolute deviation, over time for regions in Core Sound of (a) the shell length and (b) the shell height of sampled clams. Confidence intervals are based on 999 bootstrap replicates from the corresponding empirical distributions. Notice that trajectories are remarkably parallel until the rotation plan, after which variability in CO increases while variability in COC decreases.
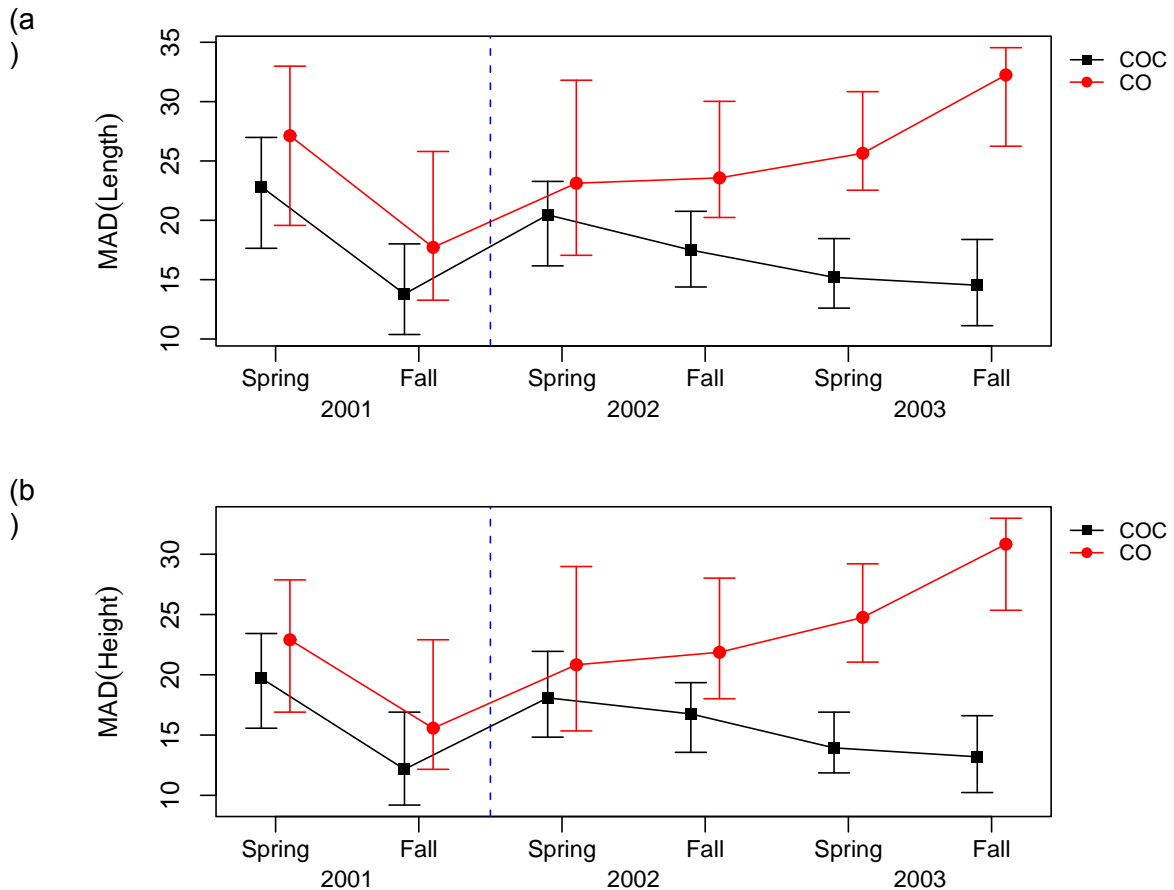
Figure 3.7. Probabilistic experiment described in the text for studying the effect of clam harvesting intensity on clam size distributions in Core Sound.
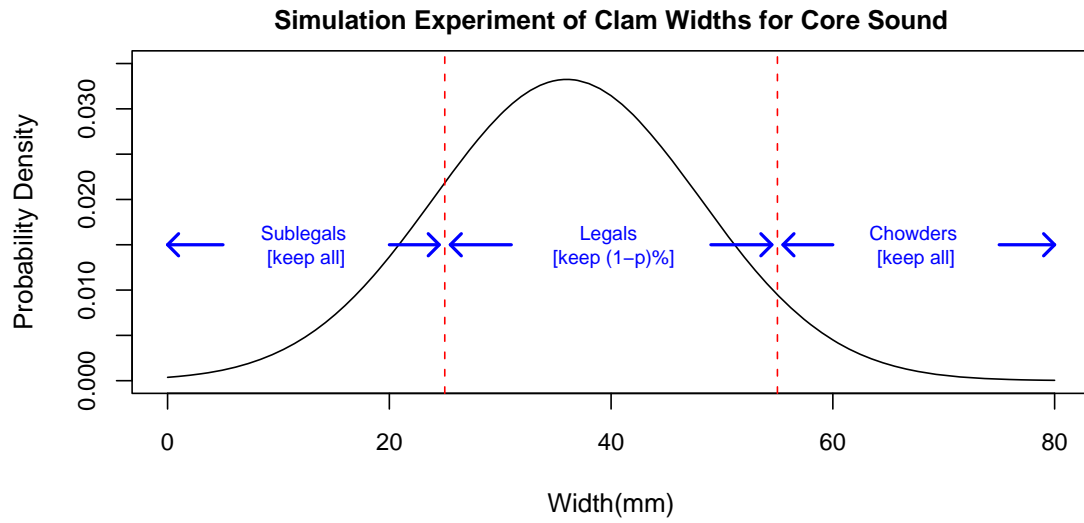
Figure 3.8. Monte Carlo results for the probabilistic experiment of Figure 4. Error bars represent 95% confidence intervals for the calculated MAD statistic.

Percent Harvest of Legal Clams (leaving sublegals and chowders)
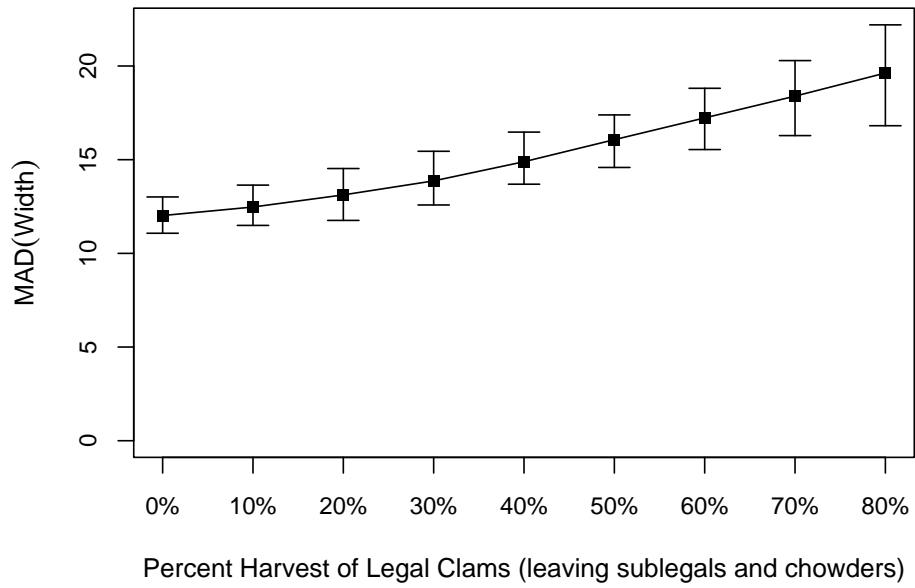
Figure 3.9. Monte Carlo results for the probabilistic experiment of Figure 3A.4. Three different scale estimates, standard deviation (SD), interquartile range (IQR) and median absolute deviation (MAD), are calculated for each random experiment. Error bars represent 95% confidence intervals for each statistic.
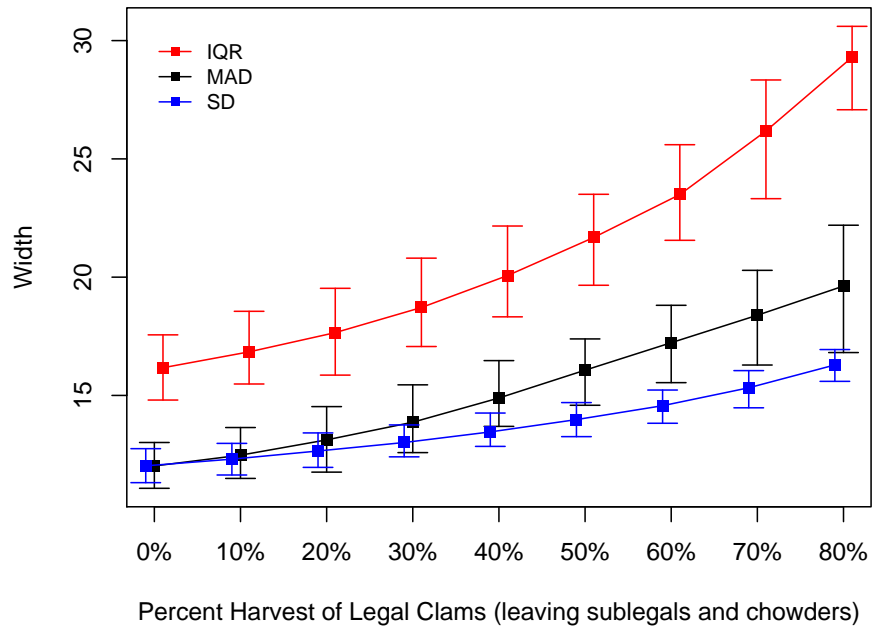
Figure 3.10. Mixtures of normal distributions chosen to represent a bimodal distribution as seen in Figs. 3.2 and 3.3 both before (a) and after (b) being subjected to 50% fishing intensity on legal-size clams (excluding chowders).

(a)

(b)
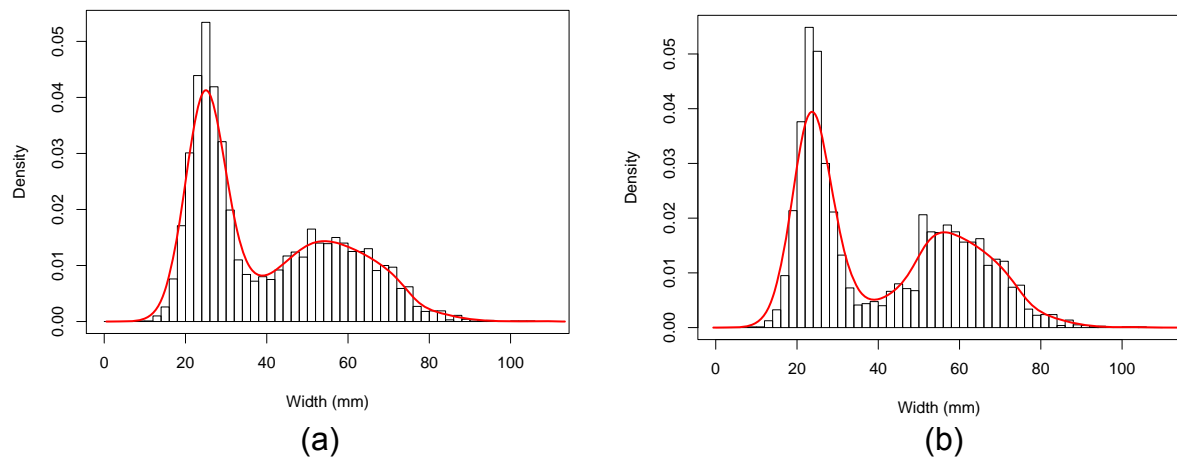
Figure 3.11. Monte Carlo results for the probabilistic experiment of Figure 3.7 but using the clam width distribution shown in Figure 3.10a. Three different scale estimates, standard deviation (SD), interquartile range (IQR) and median absolute deviation (MAD), are calculated for each random experiment. Error bars represent 95% confidence intervals for each statistic.
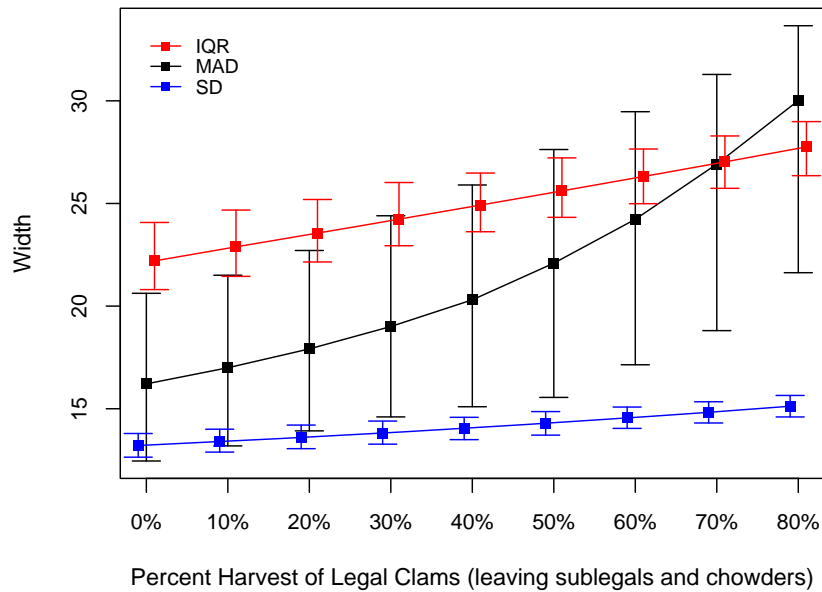
Figure 3.12. Histogram of the distribution of clam width in PCO over the course of the study.

Distribution of Width for PCO
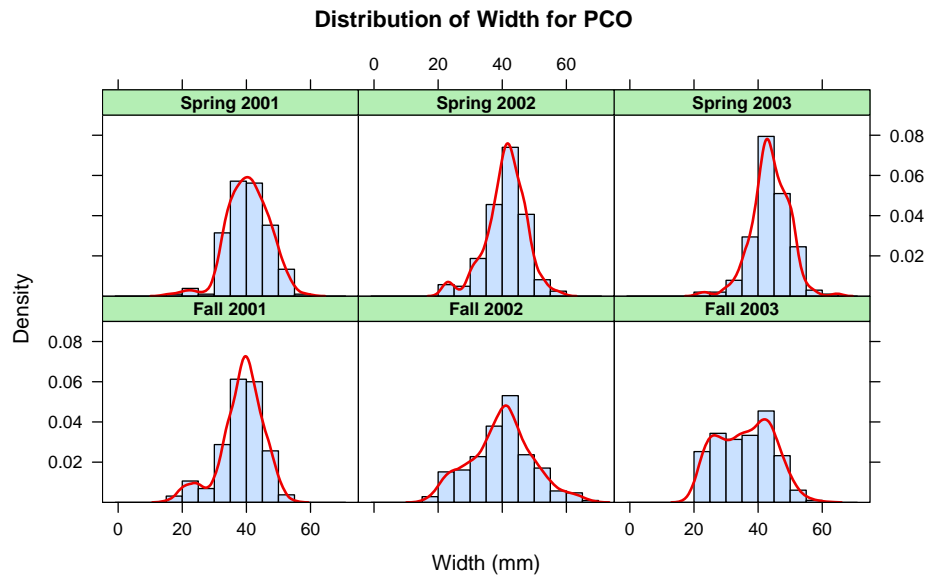
Figure 3.13. Histogram of the distribution of clam width in PC over the course of the study.

Distribution of Width for PC
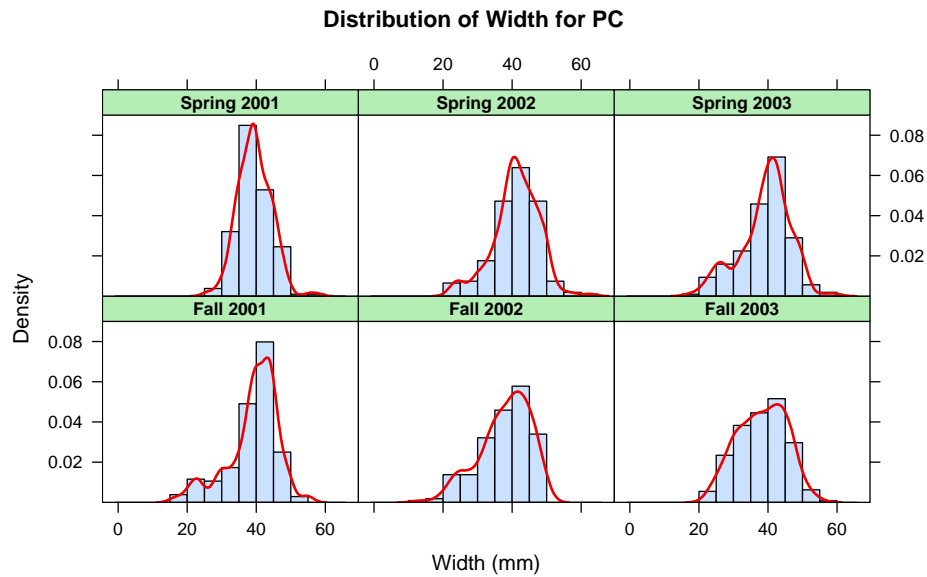
Figure 3.14. Trends in location over time for areas in Pamlico Sound based on (a) the mean, and (b) the median, a robust alternative. Confidence intervals are based on 999 bootstrap replicates from the empirical distribution.

(a)

(b)
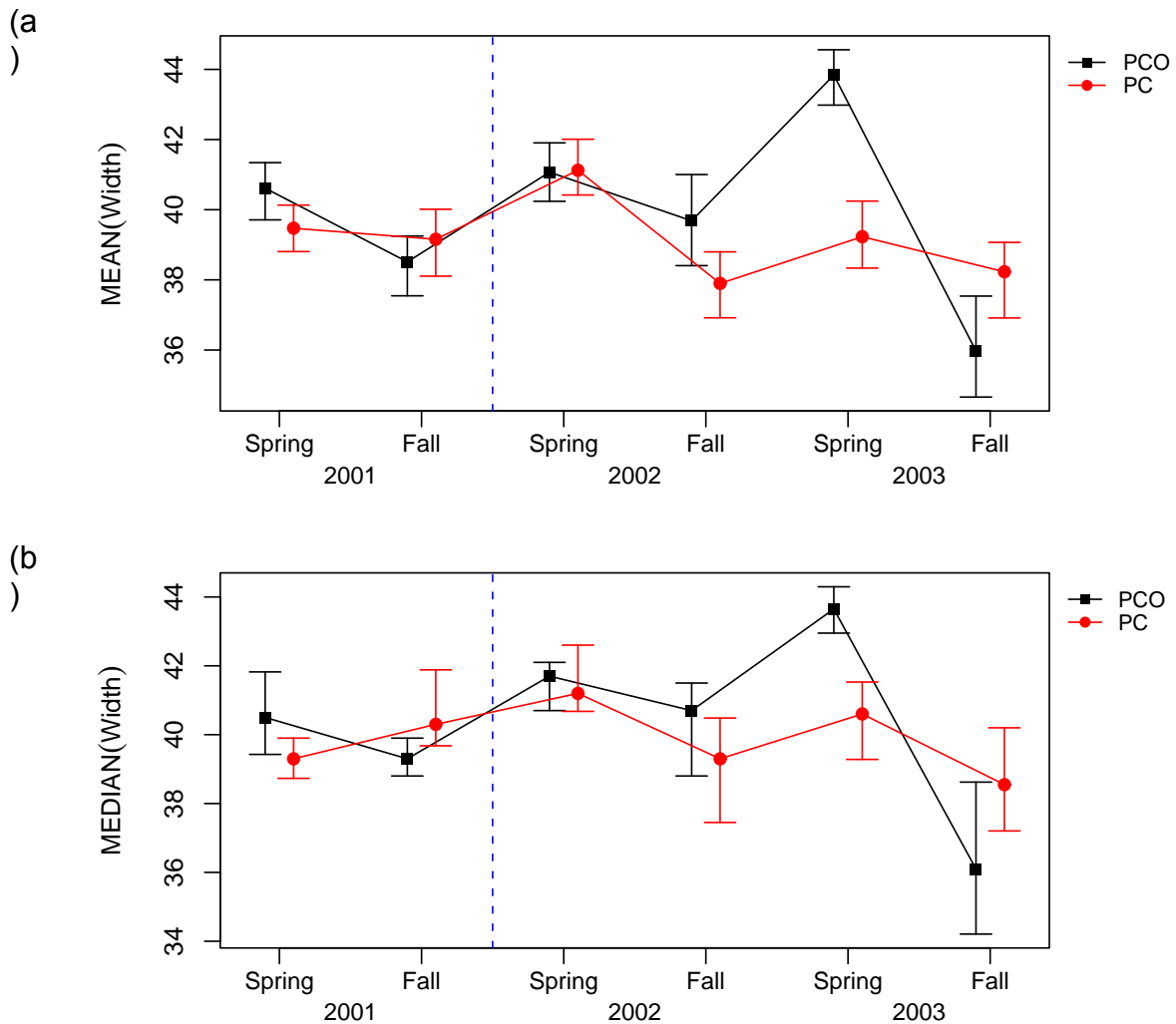
Figure 3.15. Trends in scale over time for areas in Pamlico Sound based on (a) the standard deviation, and two robust alternatives, (b) the interquartile range (IQR) and (c) the median absolute deviation (MAD). Confidence intervals are based on 999 bootstrap replicates from the empirical distribution.

(a)

(b)

(c)

156
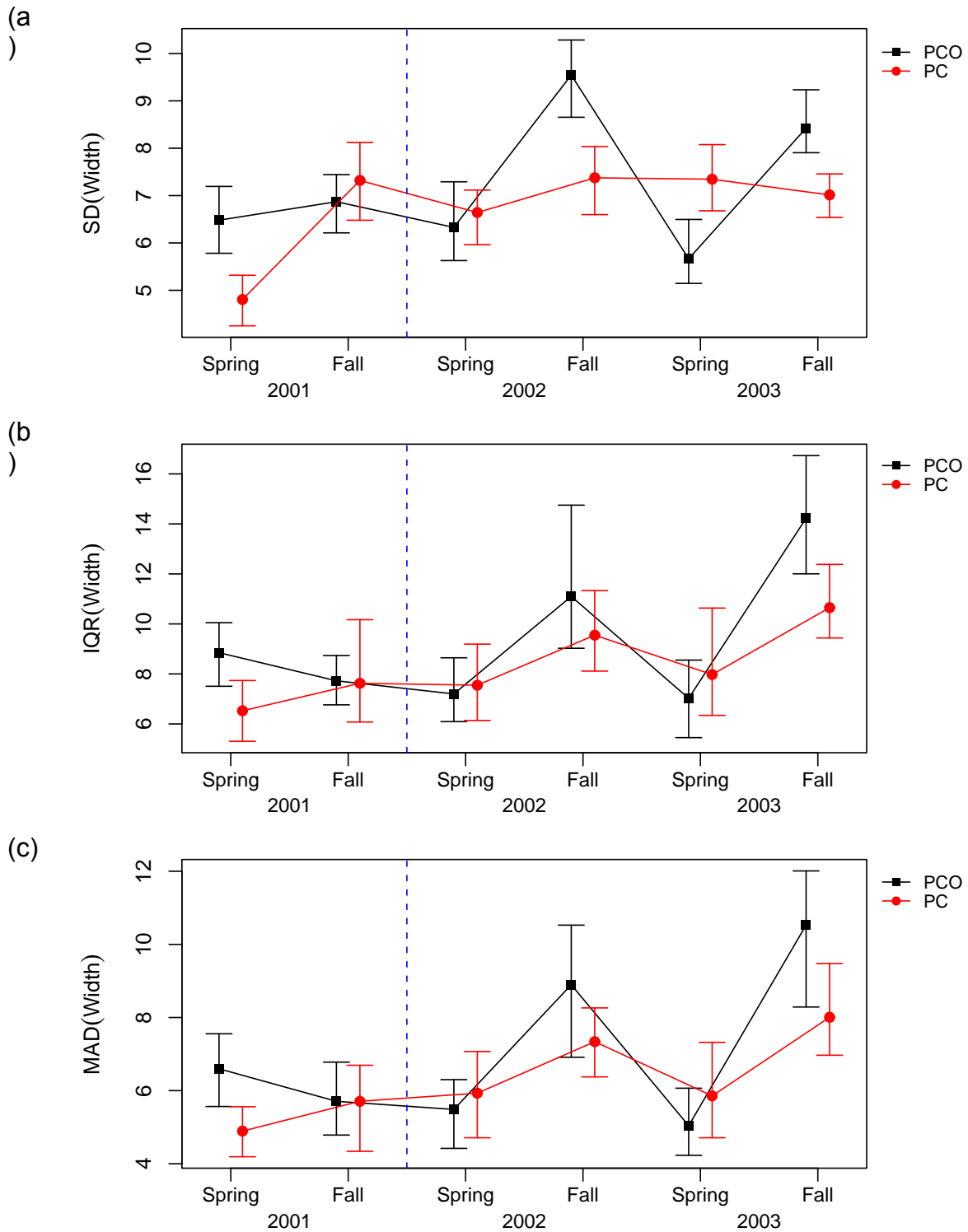
Figure 3.16. For both PCO and PC, histogram of the distribution of clam height in PC over the course of the study.

Distribution of Height for Pamlico
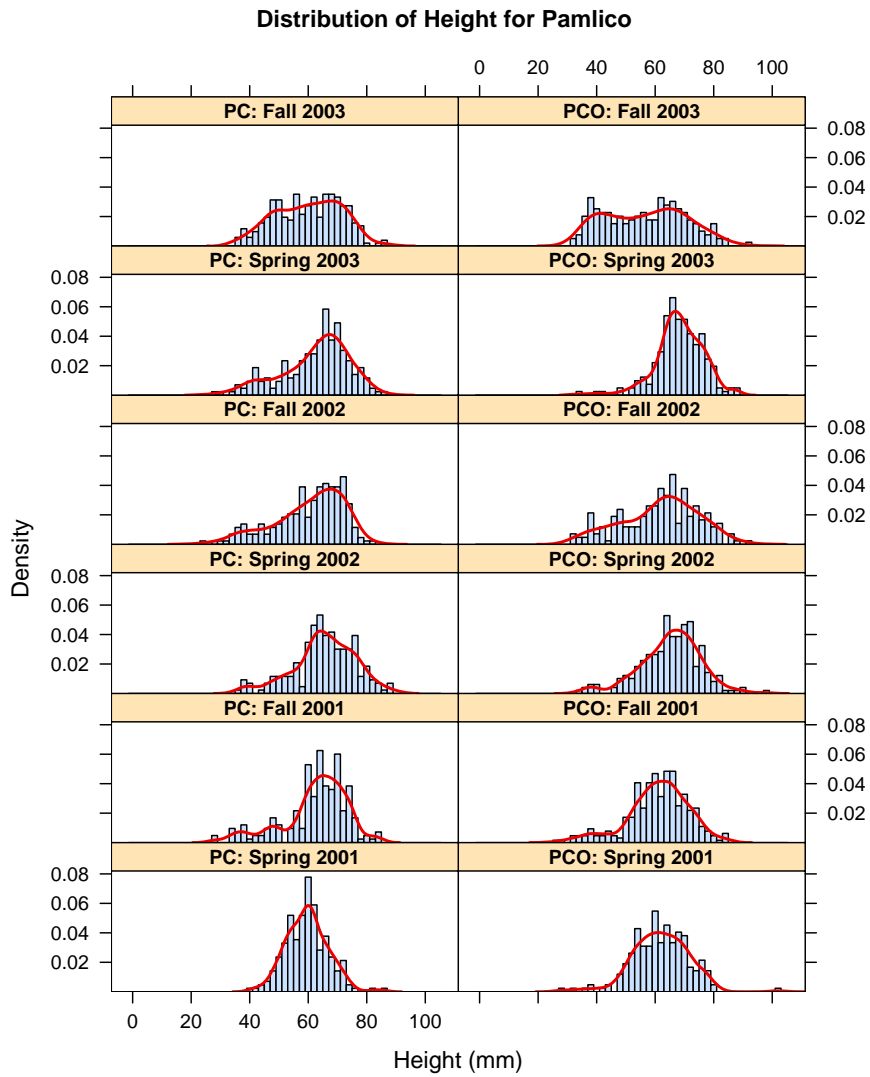
Figure 3.17. Fitted normal mixture distributions for PC and PCO in spring 2003 superimposed on a histogram of the raw data. The nonparameteric density is a smoothed histogram.

PC: Spring 2003

PCO: Spring 2003
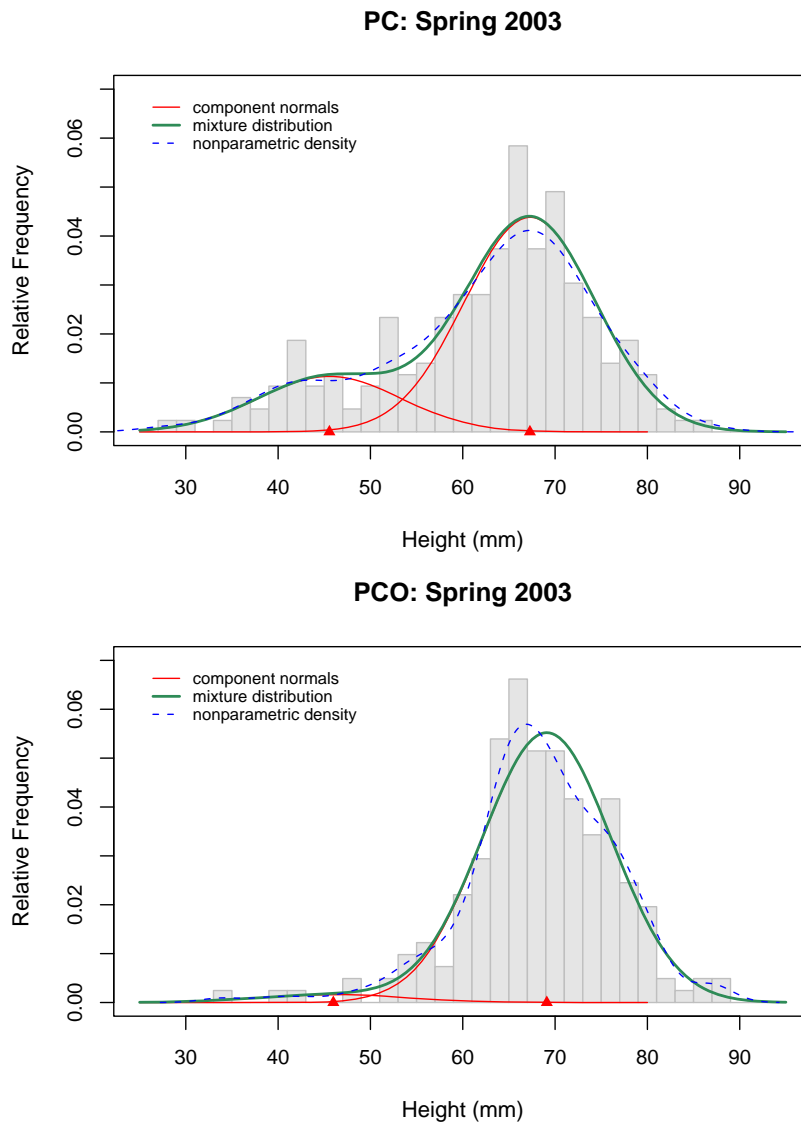
Figure 3.18. The effect of fishing pressure on clam height distribution. Figure 3.18a shows the two starting populations. Figure 3.18b shows the effect of removing 50% of the clams with widths between 25 and 50 mm. Fig 3.18c decreases the upper bound on the size range to 40 mm.
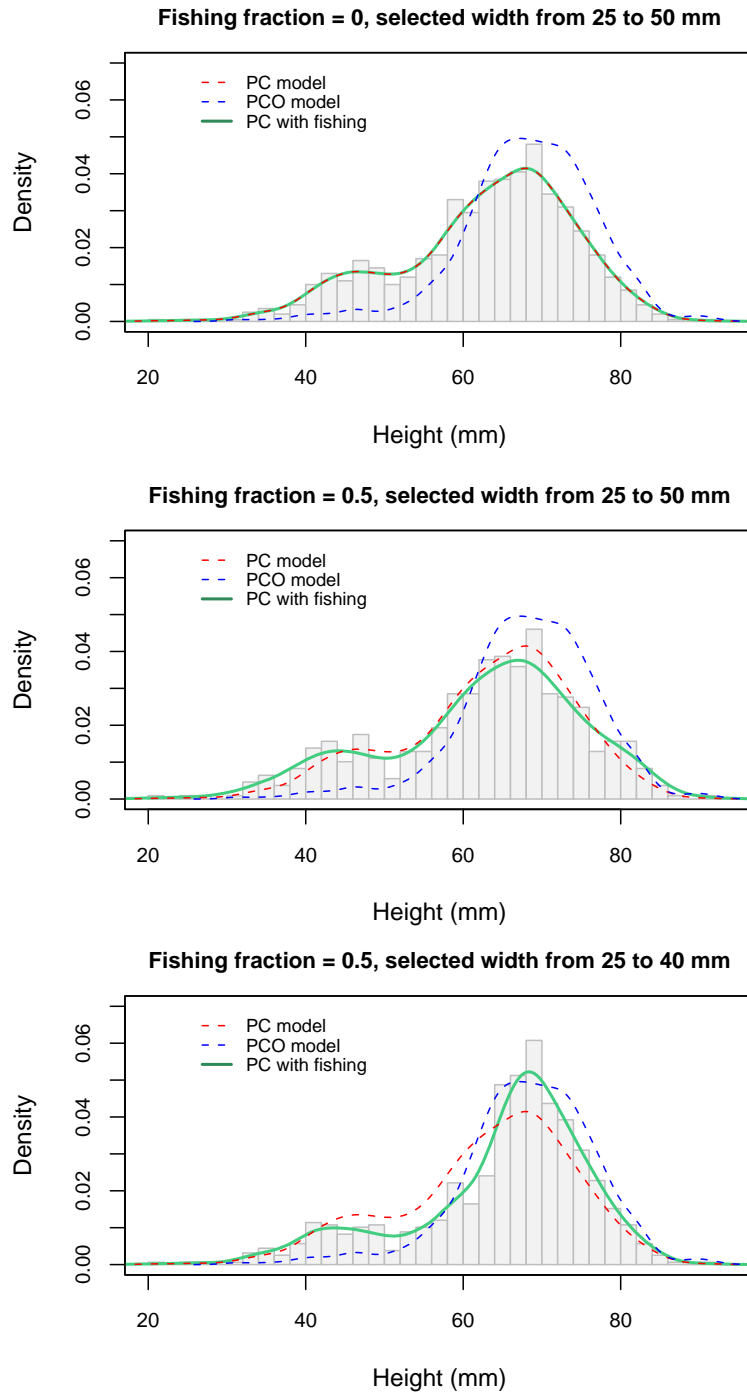
Chapter 3 Appendix.
Changes in Age and Size Structure of Hard Clam (*Mercenaria mercenaria*) Populations in Core and Pamlico Sounds as a Result of Rotating MPAs.

The Effect of Fishing on Clam Height

By spring 2003 the height distribution of clams in PC and PCO are markedly different (Figs. 3.16). Examination of histograms of the height distributions suggests a mixture of normal distributions might provide an adequate fit. This mixture of distributions can be parameterized as follows.

$$f\left(p,\mu_1,\sigma_1^2,\mu_2,\sigma_2^2\right)= pN\left(\mu_1,\sigma_1^2\right)+(1-p)N\left(\mu_2,\sigma_2^2\right) \tag{1}$$

This probability distribution is fit to the data for PC and PCO separately using maximum likelihood estimation. The fitted and empirical distributions are shown in Figure 3.17. Notice how close the estimated mixture model comes to the nonparametric density estimate. The maximum likelihood estimates of the parameters of the distribution are shown in Table 3A.1. Table 3A.1 reveals that the pairs of means and standard deviations of the normal distributions are very similar in PC and PCO. The primary difference is the size of the contribution (*p*) of the left-most normal to the overall distribution.

Table 3A.1 Parameter estimates for the normal mixture distributions shown in Figure 1

Location	p	$\hat{\mu}_1$	$\hat{\sigma}_1$	$\hat{\mu}_2$	$\hat{\sigma}_2$
PC	0.22	45.56	7.74	67.28	7.11
PCO	0.03	45.98	7.93	69.10	7.00

Formal Goodness of Fit Tests

Table 3A.2 displays the observed and fitted frequencies for the groupings used in the histograms of Figure 3.16.

Table 3A.2 Observed and expected counts for the mixture models for PC and PCO

Height Category	PC Observed Count	PC Expected Count	PCO Observed Count	PCO Expected Count
$(-\infty,27]$	0	0.4	0	0.1
(27,29]	1	0.4	0	0.1
(29,31]	1	0.6	0	0.1
(31,33]	0	1.1	1	0.1
(33,35]	1	1.6	0	0.2
(35,37]	3	2.3	0	0.3
(37,39]	2	3.0	1	0.4
(39,41]	4	3.8	1	0.5
(41,43]	8	4.4	0	0.6
(43,45]	4	4.8	0	0.7
(45,47]	5	5.0	2	0.8
(47,49]	2	5.1	0	0.9
(49,51]	4	5.1	2	1.1
(51,53]	10	5.3	4	1.6
(53,55]	5	6.0	5	2.6
(55,57]	6	7.3	3	4.2
(57,59]	10	9.4	9	6.6
(59,61]	12	12.0	12	9.8
(61,63]	12	14.7	22	13.5
(63,65]	16	17.1	27	17.3
(65,67]	25	18.5	21	20.4
(67,69]	16	18.7	21	22.2
(69,71]	21	17.4	17	22.3
(71,73]	13	15.0	14	20.6
(73,75]	10	12.0	17	17.6
(75,77]	6	8.8	10	13.8
(77,79]	8	6.0	8	10.1
(79,81]	5	3.8	2	6.7
(81,83]	2	2.2	1	4.2
(83,85]	1	1.2	2	2.4
(85,87]	1	0.6	2	1.2
(87,89]	0	0.3	0	0.6
$(89,\infty)$	0	0.2	0	0.4
Total	214		204	

Model fit is checked in two ways, using the parametric Pearson chi-square test and a randomization test. For the asymptotic chi-squared distribution to

hold, the Pearson chi-square test requires that no more than 20% of the expected counts have frequencies less than 5. Some of the categories shown in Table 3A.2 must be collapsed. The randomization test does not have such a requirement, but it also doesn't penalize for overfitting (as the Pearson test does in the calculation of degrees of freedom).

For the parametric test, I group categories from left to right when necessary until a minimum expected frequency of five is achieved. To maximize the degrees of freedom for the test and increase its power I do not combine categories that already have expected frequencies of 4 or more.

The Pearson statistic for the chi-squared goodness of fit test is the following.

$$X^2 = \frac{(O_i - E_i)^2}{E_i} \tag{2}$$

This statistic has an asymptotic χ^2_{n-1-p} distribution where *n* is the number of categories and *p* is the number of parameters estimated to obtain the expected counts. For each of the mixture models there were five parameters estimated.

For the randomization test I divide the expected counts by the total counts to obtain the expected probabilities for each category and then treat this as the empirical distribution of the data (which is a reasonable assumption if the mixture model is an adequate model). Using this empirical distribution I generate new "pseudo-observed" data and use it to calculate the Pearson statistic of eqn (2).

This process is repeated a sufficient number of times to obtain an empirical null distribution of the statistic. The observed value of the Pearson statistic is then compared to this null distribution from which a randomization p-value can then be calculated. If the actual data arose from the hypothesized model, then the calculated Pearson statistic should look like the Pearson statistics from the pseudo-observed data.

Table 3A.3 shows the results for the parametric and randomization based Pearson tests. The randomization p-value is based on 10,000 randomizations

Table 3A.3   Goodness of fit tests for the normal mixture models

Test	PC			PCO		
	X^2	df	*p*	X^2	df	*p*
parametric	16.084	16	0.4471	8.730	10	0.5579
randomization	20.577	—	0.9285	23.871	—	0.7485

As is clear from either test, there is no evidence for rejecting the fit of the mixture models to either PC or PCO.

The two models can be compared by asking the parallel questions: Does the mixture model for PC fit the data for PCO and does the mixture model for PCO fit the data for PC? Table 3A.4 gives the results of these tests.

Table 3A.4   Goodness of fit test of the normal mixture model to the "other" area: PC model to PCO data and PCO model to PC data

Test	PC model vs PCO data			PCO model vs. PC data		
	X^2	df	p	X^2	df	p
parametric	60.392	16	< 0.0001	202.854	10	< 0.0001
randomization	77.7775	—	0.0013	276.606	—	0.0001

The individual mixture models fit their own data quite well, but each is completely inadequate as a model for the other area's data.

Modeling the Effect of Fishing

Based upon the results of the previous section, it is reasonable to use a mixture model as a surrogate for the actual distribution of heights in PC and PCO. This has some immediate advantages, because I can use the mixture distributions to generate observations that can be used in simulation experiments (such as that applied to widths in Core Sound). In particular I can observe the effect of simulated fishing on the distribution of height in our simulated population.

For instance Figure 3A.1 displays the fitted mixture models superimposed on the raw data for PC and PCO (as in Figure 3.17), along with the density estimate obtained from 1000 observations randomly generated from the mixture distribution.

PC: Spring 2003
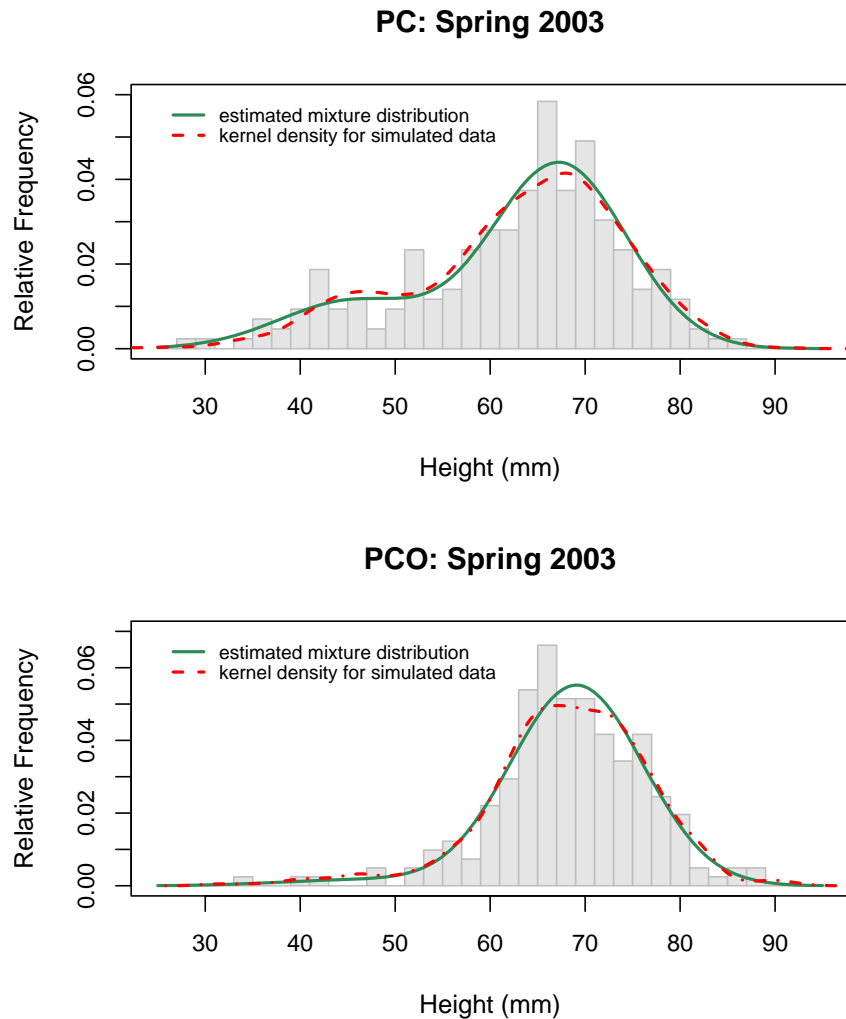
PCO: Spring 2003

Figure 3A.1. Fitted normal mixture distributions for PC and PCO in Spring 2003 superimposed on a histogram of the raw data.

Although the PC and PCO populations are spatially distinct and the results from model fitting described elsewhere indicate that in Spring 2001, Fall 2001, and Fall 2002 (but not Spring 2002) the statistical models needed to describe these areas are distinct from one, graphically the models did not appear that different.

166

Spring 2003 is the first time that the size distributions in PC and PCO looked very different from each other. Since one area is protected and the other area is opened, the observed differences in size distribution may possibly be attributed to fishing. A natural way to address this would be develop a size projection model for these clams, with and without fishing pressure, and seeing whether the two patterns shown in Figure 3.17 can be generated by starting with a single size distribution. Unfortunately this is complicated by the fact that the populations were statistically distinct in Fall 2002. A far simpler approach is to assume that if PCO were closed to fishing, its size distribution in spring 2003 would be roughly the same as the distribution observed in PC. Using the simulated data for PC in spring 2003, fishing pressure can be applied to see if the resulting distribution can be made to resemble what is actually obtained for PCO.

The three parameters that can be controlled are the fraction of the population that can be removed by fishing and the upper and lower limits of the size range of clams that can be treated as "catchable". Legal limits and market constraints are defined in terms of clam width rather than height, so it is useful to define these parameters in terms of width. As shown in Figure 3A.2, the relationship between height and width is a fairly tight one, and we use the regression equation of height on width to make the conversion from one to the other.

PC Spring 2003

$$y = 3.30 + 1.51x$$

(plot axes: Height (mm) on y-axis, Width (mm) on x-axis)
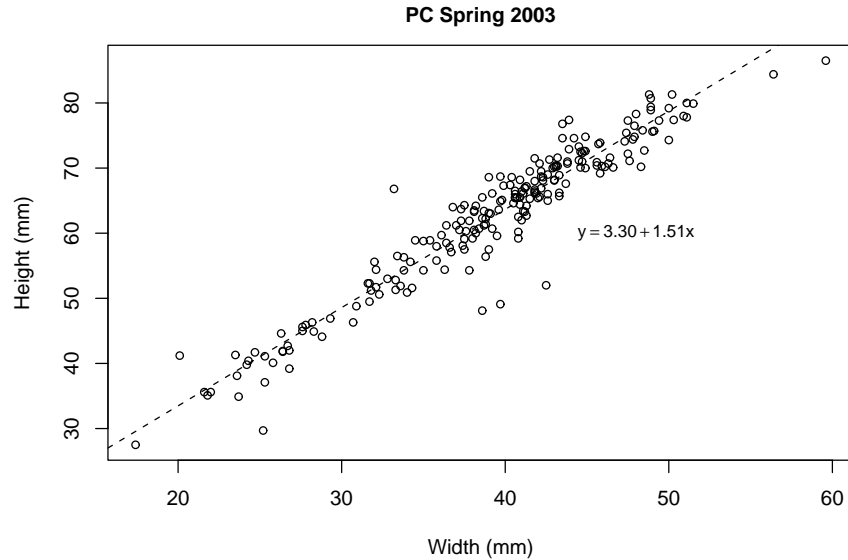
Figure 3A.2. Relating height to width in PC during Spring 2003.

Using the simulated data for PC in Spring 2003, I select upper (*u*) and lower (*l*) bounds on width (which I then convert to bounds on height using the regression equation) and a fishing fraction, *f*, and remove that fraction of the "catchable" clams from the simulated population. Then I compare the distribution that results to the actual distribution in PCO. Formal goodness of fit tests can then be applied.

Figure 3.19 shows the result for various choices of *u*, *l*, and *f*. In each plot, the red and blue curves are the kernel density estimates for data simulated using the fitted mixture models for PC (red) and PCO (blue). The green curve is the kernel density estimate for the data that result from applying fishing pressure to PC. The histogram displayed is for the fished out data (corresponding to the green curve, Figure 3A.3).   These are samples of results obtained when both size limits and fishing fractions are adjusted.

168

Figure 3A.3. Fitted mixture models.

Fishing fraction = 0.65, selected width from 20 to 39 mm

Fishing fraction = 0.5, selected width from 22 to 38 mm
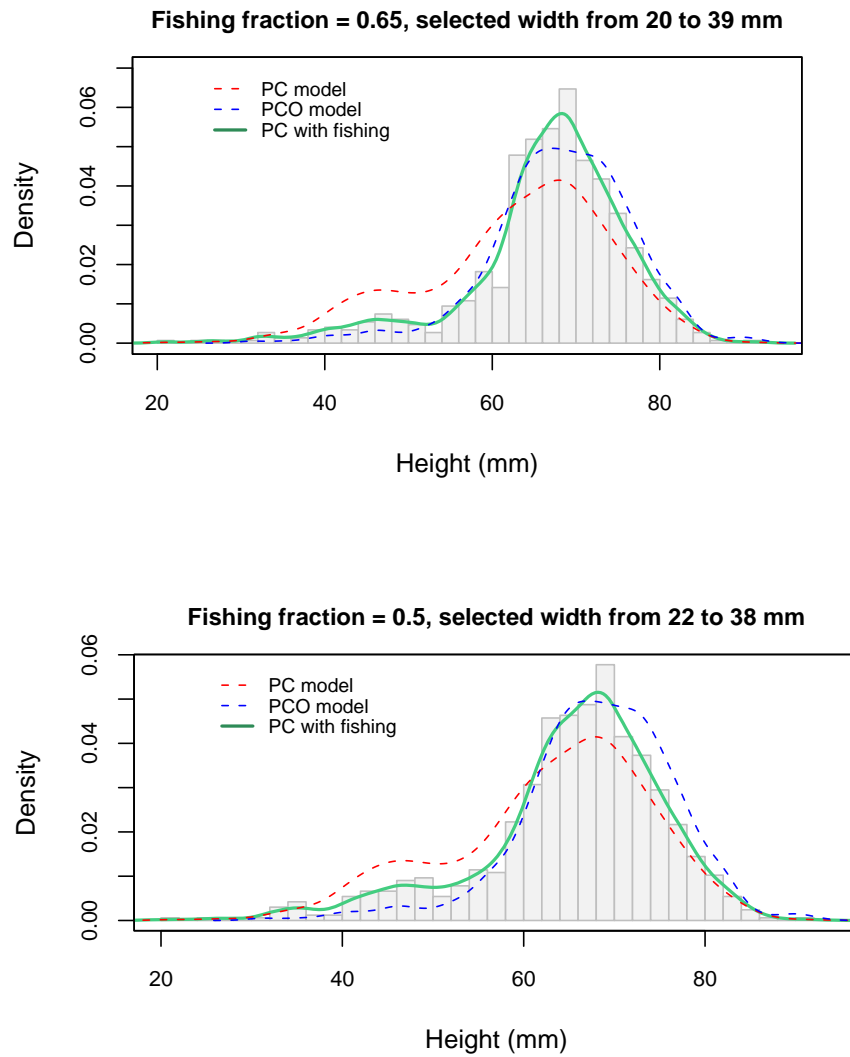
Figure 3A.3. Fitted mixture models (continued)

Fishing fraction = 0.5, selected width from 22 to 40 mm
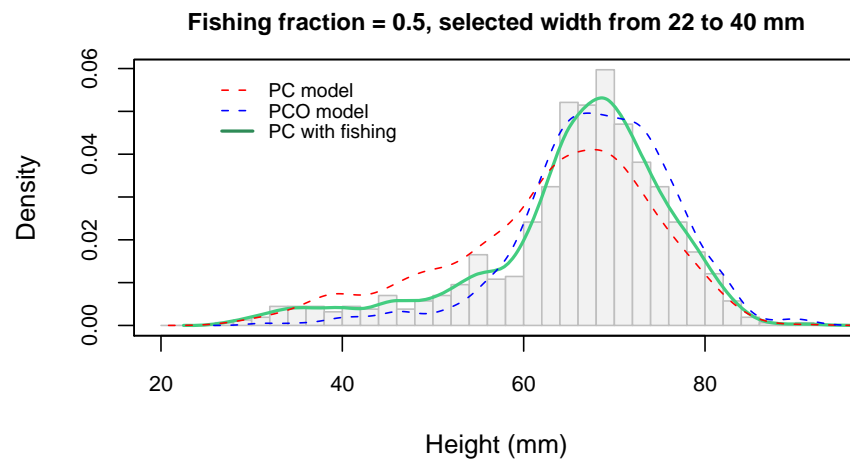
Figure 3A.4. Allometric age models for Pamlico Sound based on width.
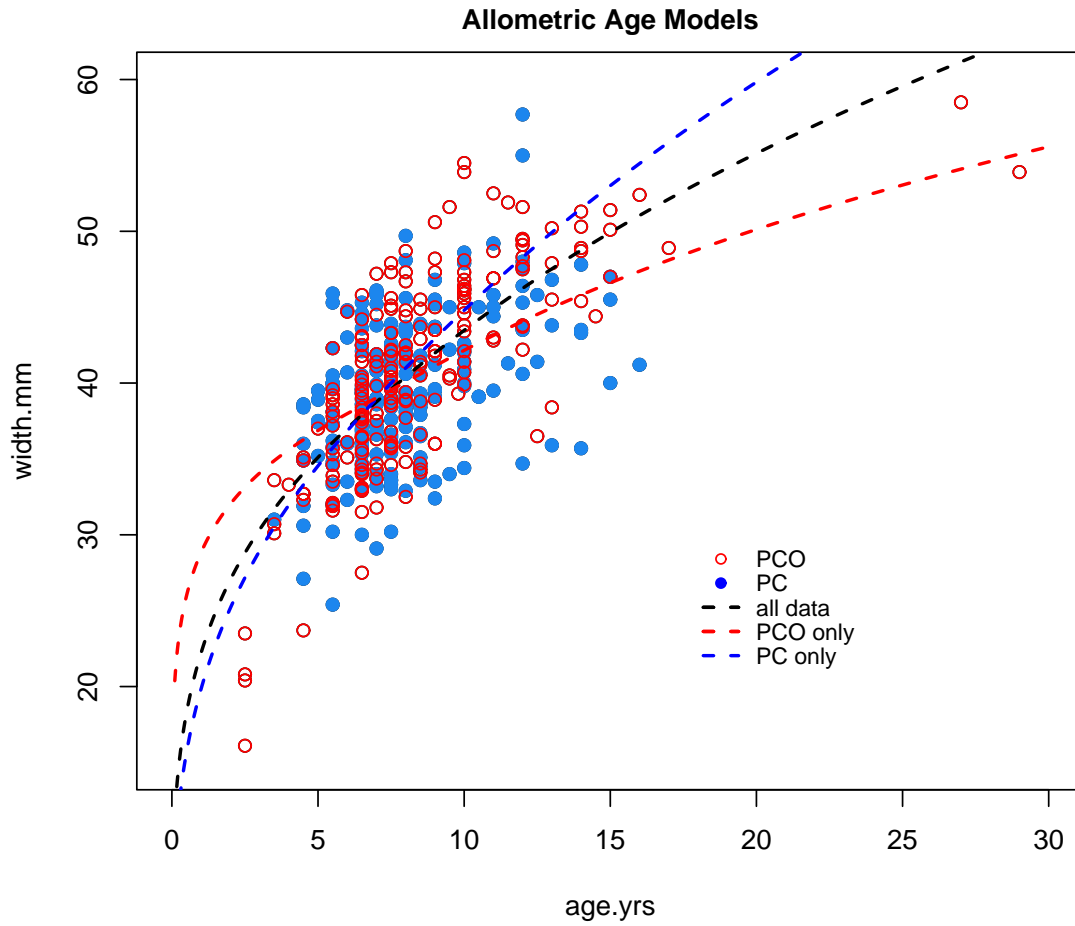
LITERATURE CITED

Fegley S. R. 2001. Demography and dynamics of hard clam populations. Pages 383-422 *In* J. N. K. a. M. Castagna, editor. Biology of the Hard Clam, Elsevier Science B. V,

Malinowski S. M. 1985. Effects of density on adult growth, survivorship, fecundity, and recruitment of northern quahogs. :79-90.

Peterson, C. H., Duncan, P. B., Summerson, H. C., Safrit,G.W.Jr. 1983. A mark-recapture test of annual periodicity of internal growth band deposition in shells of hard clams, Mercenaria mercenaria, from a population along the southeastern United States. Fishery Bulletin **81**:765-779.

Peterson C. H. 2002. Recruitment overfishing in a bivalve mollusc fishery: hard clams (Mercenaria mercenaria) in North Carolina. Can.J.Fish.Aquat.Sci. **59**:96-104.

Rice, Michael A., Hickox, Charles,Zehra, Itrat. 1989. Effects of intensive fishing effort on the population structure of quahogs, Mercenaria mercenaria (Linnaeus 1758), in Narragansett Bay. Journal of Shellfish Research **8**:345-354.

Walker R. L. 1989. Exploited and unexploited hard clam, Mercenaria mercenaria (L.) populations in coastal Georgia. Contributions in Marine Science **31**:61-75.

Chapter 4.
Investigating the function of a hard clam (*Mercenaria mercenaria*) lease in Core Sound as a spawning sanctuary.

INTRODUCTION

Protection of areas as spawning sanctuaries is becoming more prevalent, because MPAs are predicted to increase the productivity of fisheries by larval export, spillover of juveniles and adults into surrounding areas, and ecosystem protection (Agardy 1994, Allison *et al.* 1998, Bohnsack 1993, Duganand Davis 1993, Lauck *et al.* 1998, Roberts 1995, Russ and Alcala 1996a, Russ and Alcala 1996b). Criticism of the use of MPAs for fisheries management results from a lack of studies that demonstrate enhanced recruitment within or outside the boundaries of the reserve. There are a limited number of studies that provide indirect evidence of settler enhancement outside spawning sanctuaries. These include Hockey and Branch (1994), who found patterns of increasing densities of juvenile limpets with proximity to the boundary of an MPA in the Canary Islands, and Peterson *et al*. (1996), who observed the apparent success of using local spawning sanctuaries to restore bay scallop abundance within an estuary in central North Carolina. Discoveries have shown that some marine populations such as coral reef fishes may be self-recruiting in which larvae are locally

retained or return as juveniles to the spawning site (Jones *et al.* 1999, Swearer *et al.* 1999).

I investigated the function of a large clam lease in southern Core Sound along Core Banks (Huber lease #9201) as a sanctuary for reproducing adults in supplementing the surrounding clam populations. Although there are many leases on the mainland side, this lease is the only one located on the banks side of southern Core Sound. Created in the mid-1990's, the seven-acre clam lease protects great numbers of *M. mercenaria notata*, the hatchery or aquaculture variant of the hard clam that is morphologically and genetically distinct (although it originally was a wild-type variant). When the clams reach market size they are removed from the lease (Figure 4.1). On the lease, there were 5.5 million clams from 1995 to 1998, 1.0 million clams from 1999 to 2001 and 0.5 million clams in 2002 (Huber pers. comm.). Presumably the clams spawn and export larvae to surrounding areas. Therefore, I sampled for offspring marked with *notata* on transects centered on the lease site but extended north and south to a maximum distance of 8 km along axes of primary current flow.

To test the possibility that post-settlement processes are differentially reducing the population of *notata* clams and affecting their distribution and abundances, I performed a set of predator-prey experiments in field enclosures in Middle Marsh near Beaufort, NC, during the summer of 2002. The predator was the stone crab *Menippe mercenaria*. Stone crabs possess very large, strong claws that are able to crack the robust shells of hard clams

174

RESEARCH QUESTION

Do spawning sanctuaries replenish surrounding harvested areas by increasing recruitment?

Specifically:

Does the population of aquaculture (*notata*) clams on the Huber clam lease supplement the surrounding wild population by exporting larvae?

METHODS

Notata markings persist until clams are approximately 4 years old (so there is a portion of the adult *M. mercenaria notata* population that expresses them) and also express themselves in nature, so visual methodology is a good test for tracking the offspring of marked adults (Hilbish pers. comm.). Chanley (1961) reported that the *notata* trait is controlled by a single allele or tightly linked group of alleles that are inherited in Mendelian fashion. Hatchery seed clams purchased from aquaculturists are marked by the *notata* trait in the Mendelian ratio of approximately one homozygous marked : two heterozygous marked : one homozygous unmarked (Powers pers. comm.). Therefore one-quarter of them do not have the morphological markings. There is no evidence suggesting that younger clams (less than 4 years old) that I collected would carry the *notata* gene yet not express the markings, except for the expected 25% homozygous recessives.

Experimental Design

This portion has been divided into 4 parts:

Part 1. Sampling for *M. mercenaria notata* recruits by suction dredge.

Part 2. Sampling for *M. mercenaria notata* adults and juveniles by clam rake.

Part 3. *Notata* clams caught during kicking sampling.

Part 4. Predator-prey experiments with stone crabs and wild-type and/or *notata* clams.

Part 1. Sampling for *M. mercenaria notata* recruits by suction dredge.

I searched for *notata* recruits along Core Banks to the north and south of the clam lease in fall 2001, fall 2002 and fall 2003. Sampling occurred in the fall because, by then, the recruits that settled in the summer are large enough to catch (Peterson *et al.* 1983). I chose areas that had seagrass beds along transects that were approximately 0.25 km, 0.5 km, 1.0 km, 2.0 km, 4.0 km, and 8.0 km to the north and south of the lease. I sampled the transects in random order. At each transect I sampled three sites, taking three replicate samples in the middle of the seagrass, at the edge of the seagrass, and in the sand flat adjacent to the outer edge of the seagrass for a total of nine samples. I suction dredged for recruits using a 0.5-m^2 quadrat to a minimum depth of 10 cm retaining the samples in 3.0-mm mesh bags, summing to a total of 4.5m^2 of bottom per transect. I noted the presence of seagrass and oyster cultch (shell) and general sediment type. I recorded GPS location and the actual distance from the lease, water depth, surface water temperature, salinity and time of day. At the lab, I measured *M. mercenaria* recruits and recorded any *notata*.

Part 2. Sampling for *M. mercenaria notata* adults and juveniles by clam rake.

Since the clam lease was established in the mid-1990's, I searched for

marked clams that may have settled as larvae exported from the lease in previous

years. External *notata* markings persist on the clams until approximately four years

of age (Hilbish pers. comm.). I sampled in the seagrass beds along Core Banks

using a specially constructed clam rake with knives as tines placed ¾ inch apart. In

fall 2001, I used the same transects as for dredging, which were at distances of 0.25

km, 0.5 km, 1.0 km, 2.0 km, 4.0 km, and 8.0 km from the lease. I raked 4 m^2 both at

the interior and the edge of the seagrass bed (8m^2 per transect) for a total area that

fall of 96 m^2. I counted and retained any hard clams, noting any *notata* and counted

and returned other organisms present.

In fall 2002 and fall 2003 I increased my efforts to find marked clams. At

each transect, I raked 50 m^2 at both the interior and the edge of the seagrass for a

total area of 100 m^2 per transect. The total area of bottom that I raked during the

two years was 1225 m^2. I retained all *M. mercenaria* searching for *notata* markings.

Part 3. *Notata* clams caught during kicking sampling.

While I was carrying out kicking sampling for the rotation plan (McDaniel

unpub.), I noted any *notata* that I caught in my samples. I sampled for 3 years in

both spring and fall (2001, 2002, and 2003).

**Part 4. Predator-prey experiments with stone crabs and wild-type and/or
notata clams.**

While breaking open wild-type and *notata* clams for gonad analysis for a different experiment, I noticed that the *notata* shells were much easier to crack. Therefore I hypothesized that *notatas* may be easier for predators to break open as well, and that this may be reducing their abundances in the wild and affecting my ability to find them.

To determine if there was differential predation on wild-type versus *notata* clams, I carried out a series of predator-prey experiments. The prey included four different types of *M. mercenaria*: wild-type (unmarked) and the three hatchery morphs: homozygous *notata*, heterozygous *notata*, and unmarked. I attempted to use clams that were similar in size (about 30 mm in width); however, I was restricted by what I could find in the wild and sizes that the clam dealer could provide. The predator was the stone crab, *Menippe mercenaria*, which I caught using crab pots. In seagrass habitat in Middle Marsh, Beaufort, NC, I planted blocks of four square 1.0 X 1.0 X 0.8 m bottomless enclosures of ½-inch galvanized hardware cloth and PVC to a depth of approximately 15 cm and labeled them Treatments A-D (Figure 4.2). To test feeding rates of stone crabs upon hatchery versus wild-type clams, Treatment A had one stone crab and six hatchery clams (two homozygous, two heterozygous, and two unmarked) and Treatment B had one stone crab and six wild-type clams. To observe prey choice, Treatment C had one stone crab and three hatchery clams (one of each type) and three wild-type clams. To measure differential survival of and my ability to retrieve the clams, Treatment D had no stone crab and three hatchery clams (one of each type) and three wild-type clams. I randomized the positions of each cage within each block.

I ran the experiment sequentially with two concurrent blocks, each time moving to a new area of seagrass for a total of 16 blocks and 64 cages, 48 of them with stone crabs. I gently removed any bivalves that were on the sediment surface. I marked, measured, and buried the clams in life position, allowing them to burrow before I added the stone crabs, of which I had measured the length. I removed the crabs after 48 hours, noting which ones had escaped, and climbed into the enclosures in order to systematically search the sediment with my fingers and retrieve live clams and shell pieces. At the lab, I reconstructed what had happened from the pieces – the clams were often pulverized by the crabs and there were many shell pieces.

ANALYSES AND RESULTS

Part 1. Sampling for *M. mercenaria notata* recruits by suction dredge.

In fall 2001, fall 2002, and fall 2003 I found 17 recruits combined (Table 4.1). I found 2 live *notata* clams (both in 2001), 1 of them a recruit (approximate length <10mm) and 1 a sublegal (length => 10mm but < 45mm) obtained from the transect 2.0 km north of the lease. Of the recruits I found, the 1 *notata* comprised 6% of the sample.

Part 2. Sampling for *notata* adults and juveniles by clam rake.

In fall 2001, I found a total of 155 *M. mercenaria* including one sublegal clam with heterozygous *notata* or 0.7% of the population. In fall 2002, I found a total of 225 clams including six adult *notata* (four heterozygous and two homozygous) or

2.7% of the population. In fall 2003, I found a total of 289 clams including 4 adult

notata (all heterozygous) or 1.4% of the population. Overall, the *notatas* comprised

2% of the population.

Part 3. *Notata* clams caught during kicking sampling.

Figure 4.3 depicts the percentages of *notata* clams (presumably less than

approximately 4 years old because they still retain the markings) caught during clam

kicking sampling from all 4 treatments during the 6 sampling periods. The average

value was 1.42%, and ranged from 0.00% to 2.86% of the population. With one

exception, there were higher percentages of *notata* in Core Sound (both opened and

closed treatments) than in Pamlico Sound (both opened and closed treatments), but

this was not tested for significance.

Part 4. Predator-prey experiments with stone crabs and wild-type and/or *notata* clams.

Table 4.2 contains the overall results for the experiment of all blocks

combined. In Treatment A (one stone crab and six *notata* clams), 52% of *notata*

clams were eaten (61% of the heterozygous, 50% of the homozygous, and 54% of

the unmarked). For Treatment B (one stone crab and six wild-type clams), 59% of

the wild-type clams were eaten. For Treatment C (one stone crab and three *notata*

clams, one of each type, and three wild-type clams), 43% of the total clams were

eaten - 48% of the wild-type and 38% of the *notata*. For Treatment D (no stone crab

and three *notata* clams and three wild-type clams), I had 100% retrieval of clams but

only 92% of the clams survived. Sixty-three percent of the clams that died were wild-type and 37% were *notata*.

I first focus on Treatments A and B, the feeding rate comparison. Figure 4.4 is a comparison of Treatments A and B graphing the proportion of clams eaten versus block number. The mean widths and lengths of the *notata* clams are graphed in Figure 4.5. I ran a logistic regression model on Treatments 1 and 2, to analyze feeding rates of stone crabs upon aquaculture versus wild-type clams. The basic model assumes that p = probability a clam is eaten. It is a logistic regression where the logit, or log odds, is modeled as a linear function of the predictors.

$$\log \frac{p_j}{1 - p_j} = \beta_0 + \beta_1 x_{1j} + \beta_2 x_{2j} + \beta_3 x_{3j}$$

where x_1, x_2, x_3 are various predictors of interest and j denotes the value of that predictor for observational unit j. The sign of the predictors has a direct interpretation in terms of probability. A positive coefficient means an increase in the predictor increases the odds of being eaten, while a negative coefficient means an increase in the predictor decreases the odds.

To account for the structure of the experiment and at the same time to allow for observational heterogeneity a blocking variable is included in the model as a random effect. The basis model is

$$\log \frac{p_{ij}}{1 - p_{ij}} = \beta_0 + \beta_1 x_{1ij} + \beta_2 x_{2ij} + \beta_3 x_{3ij} + u_{0i}$$

where now *i* references the block and *j* references the observation in that block. Here u_{0i} is the random (subject-specific) effect for block *i* and is a term all observations from that block share where I assume $u_{0i} \sim N\left(0, \tau^2\right)$. The presence of this term makes observations within a block similar to each other and more different from observations from other blocks.

Obtaining maximum likelihood estimates of parameters from the marginal likelihood involves integrating over the random effects. An adaptive Gaussian quadrature method is used as implemented in the SAS software Proc NLMIXED (SAS Institute 2004). Model quality can be assessed using AIC (this is used in place of an ANOVA). With small samples AIC may perform poorly for model selection so a bias correction is usually recommended. The bias-corrected AIC, denoted AIC_C, is calculated as follows.

$$\text{AIC}_c = \text{AIC} + \frac{2K(K+1)}{n-K-1}$$

Here *n* is the number of observations (81 in this case) and *K* is the total number of parameters, including variance components and their correlations, estimated in the model. For AIC_C values to be comparable *n* must be the same for all fitted models. Table 1 reports the AIC_C, AIC, loglikelihood, and the number of parameters for each fitted model. Smaller values of AIC_C are preferred. Models are

ranked from best (top) to worst (bottom) using AIC_C (Table 5.3). The number of

parameters is *k*.

The AIC_C-best ranked model (Model 10) includes crab (length), (clam) width,

(clam) length, and the interaction of (clam) length and width. This is barely better

than a model (Model 9) that omits the interaction. Also looking at the Wald test for

the interaction it would not be declared significant at the .05 level. A likelihood ratio

test would also fail to find the interaction significant

LR test: 1-pchisq(2*(-53.30+54.95),1) = 0.06927988

Parameter estimates from Model 9 and Model 10 are in Tables 4.4 and 4.5, respectively.

I then combined the results of Treatments A, B, and C in order to determine overall proportions of wild-type versus aquaculture clams eaten. For the *notata* clams, 68 out of 144 total, or 46% were consumed by the crabs. For the wild-type, 80 out of 144 total, or 54% were killed by the crabs. The Mantel-Haenszel chi-square test, based on counts, provided a value of 1.9946 and a p-value of 0.1579 (df=1). An odds ratio was calculated to determine a point value and confidence interval (C.I.). The ratio of mortality of *notata* to wild-type clams was equal to 85% (a *notata* had only 85% of the chance of being eaten compared to a wild-type) and the C.I. ranged from 68-101% as an indication of the amount of spread around this point value.

For Treatments A, B and C, I created a general model in which I added variables in order to determine their impacts on the results. From this model I determined that the 2 factors affecting clam mortality and accounting for much of the difference behind the nearly significant chi-square value were the length of the crab and if the crab remained in the cage until the end of the experiment.

DISCUSSION

Part 1. Sampling for *M. mercenaria notata* recruits by suction dredge.

The small number of recruits that I found overall overall (n=17) makes it difficult to draw any conclusions. In this sample, I found 1 *notata* which was 6% of the sample. In South Carolina, *M. mercenaria notata* specimens comprised between 0.71% and 2.17% of the hard clam populations in eleven locations, so the best estimate of their relative abundance is 1.23% (Eldridge *et al*. 1976). Because this study is a few decades old, I consider this value to be the background level of *notata* in the population before augmentation by leases would have occurred. Using the binomial distribution and the assumed background level of .0123, the p-value (at the .05 level) for finding 1 or more *notata* clams =.1897, and the p-value for finding 2 or more = 0.0182. Therefore, I would have needed to find 2 *notata* clams for this value to be significantly different from the background level.

Part 2. Search for *M. mercenaria notata* adults and juveniles by clam rake.

I found 11 *notata* clams overall. The percentages of *notata* in the fall 2001, 2002 and 2003 samples were 0.7, 2.7, and 1.4 respectively. The average of these was 1.6%. Using the binomial distribution and the assumed background level of .0123, the p-value (at the .05 level) for finding 11 or more *notata* clams = .2063, and the p-value for finding 14 or more = 0.0404. Therefore, I would have needed to find 14 *notata* clams for this value to be significantly different from the background level.

Part 3. *Notata* clams caught during kicking sampling.

185

The values ranged from 0.00% to 2.86% of the population. Ten of the eleven highest percentages are found in COC and CO, which are much closer to all the clam leases in southern Core Sound (not only the Huber lease) so it is expected that there would be more *notata* found in these areas if larval export is occurring. Further analysis will include calculating a p-value for the Core Sound *notata* clams obtained by clam kicking.

For future analyses, Fisher's method of combining independent probabilities can be used to perform a meta-analysis on these three datasets combined. All three ratios (from suction dredging recruits, raking, and kicking) went in a direction suggesting higher frequencies of *notata* than the putative background frequency of 1.23%, yet none was significantly higher. However, combining the three independent p-values into a single test of the hypothesis will result in more power and perhaps even significance. On the other hand, the estimated augmentation is not as great as 1%, so these leases did not contribute substantially to recruitment outside them.

Part 4. Predator-prey experiments with stone crabs and wild-type and/or *notata* clams.

There is no preferential predation of stone crabs on the *notata* versus wild-type clams and the feeding rates of stone crabs upon *notata* vs. wild-type clams are similar. Size ranges are greater for wild clams than for *notata* because the *notata* clams were purchased from an aquaculturalist and are from the same cohort. AICc rankings of a logistic regression model run with different sets of parameters leads to the conclusion that for Treatments A and B, treatment, clam length and clam width

186

are highly correlated. Results of a Mantel-Haenszel chi-square test were close to significant for Treatments A, B and C combined (wild clams eaten more than *notata*). Much of the difference of the chi-square value is due to 2 factors: whether the crab stayed in the cage and the size of the crab.

Chapter 4 Figures.
Investigating the function of a hard clam (*Mercenaria mercenaria*) lease in Core Sound as a spawning sanctuary.

Figure 4.1. A specimen of heterozygous *M. mercenaria notata,* the most common genotype and phenotype. Note the zigzagged pattern. *M. mercenaria notata* is also referred to as a hatchery or aquaculture clam, as this wild-type variant was bred for fast growth as well as the distinctive markings. Clammers called these "hybrids" during my clam kicking sampling.

Figure 4.2. A block of the 4 treatments of the predator-prey experiment with stone crabs and either *notata* and/or wild-type clams.

Treatment A

1 crab
6 *notata* clams
(2 of each type)

Treatment B

1 crab
6 wild clams

Treatment C

1 crab
3 *notata* clams
(1 of each)/
3 wild clams

Treatment D

0 crabs
3 *notata* clams
(1 of each)/
3 wild clams
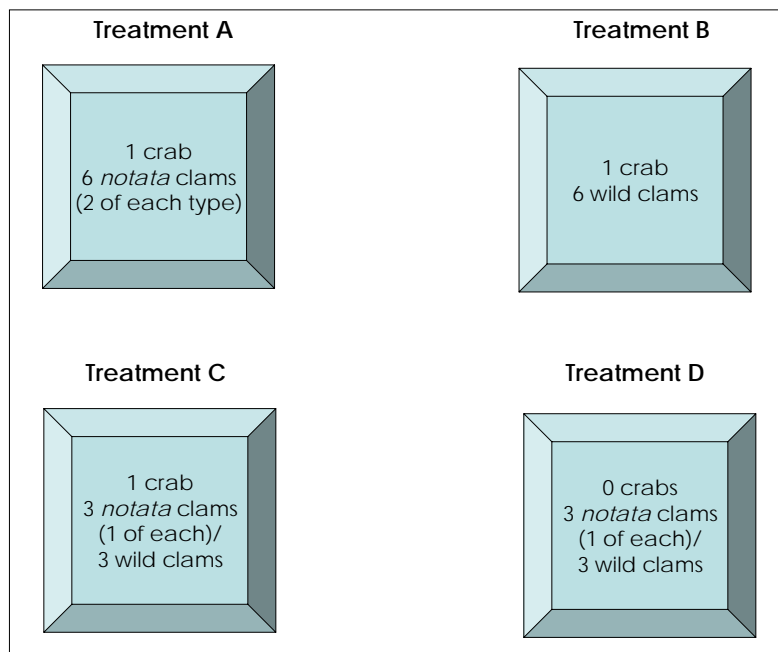
Table 4.1. The counts of clam recruits found during suction dredge sampling in fall 2001 and 2002. For each transect, there are 3 sites with 3 replicates each for a total of 9 samples (4.5m^2). The distances are from the clam lease. I looked at dead clams to increase the probability of finding *notata*, however I did not note wild-type dead clams.

TRANSECT	Legal 2001	Legal 2002	Sublegal 2001	Sublegal 2002	Recruits 2001	Recruits 2002	*Notata* 2001	*Notata* 2002
South (.25km)	2	4	0	0	0	0	0	0
South (.50km)	1	2	0	0	0	0	0	0
South (1.0km)	1	1	0	0	1	1	0	0
South (2.0km)	1	0	1	0	0	0	0	0
South (4.0km)	1	0	0	0	0	0	0	0
South (8.0km)	0	0	0	0	0	0	0	0
North (.25km)	0	0	0	0	0	1	0	0
North (.50km)	3	0	0	0	0	0	0	0
North (1.0km)	0	2	1	0	0	0	1Dead Recruit	0
North (2.0km)	2	0	3	0	0	0	2 Live: Recruit &Sub	0
North (4.0km)	0	5	6	1	3	3	0	0
North (8.0km)	0	1	3	1	6	2	1Dead Recruit	0
TOTALS	11	15	14	2	10	7	2 Live, 2 Dead	0

190

Figure 4.3. Percentages of *M. mercenaria notata* in the kicking samples for all 4 treatments and 6 sampling periods. Note that except for fall 2001 where PCO and CO have equivalent percentages, Core Sound (COC and CO) has higher values than Pamlico Sound (PCO and PC).

Core and Pamlico Sounds: Notata Clams Harvested during Kicking Sampling

	SPR 2001	FALL 2001	SPR 2002	FALL 2002	SPR 2003	FALL 2003
CO	0.64%	0.53%	2.19%	1.31%	1.07%	0.46%
COC	0.00%	1.59%	2.22%	2.86%	0.85%	0.42%
PC	0.06%	0.24%	0.45%	0.35%	0.11%	0.24%
PCO	0.08%	0.53%	0.15%	0.84%	0.00%	0.00%
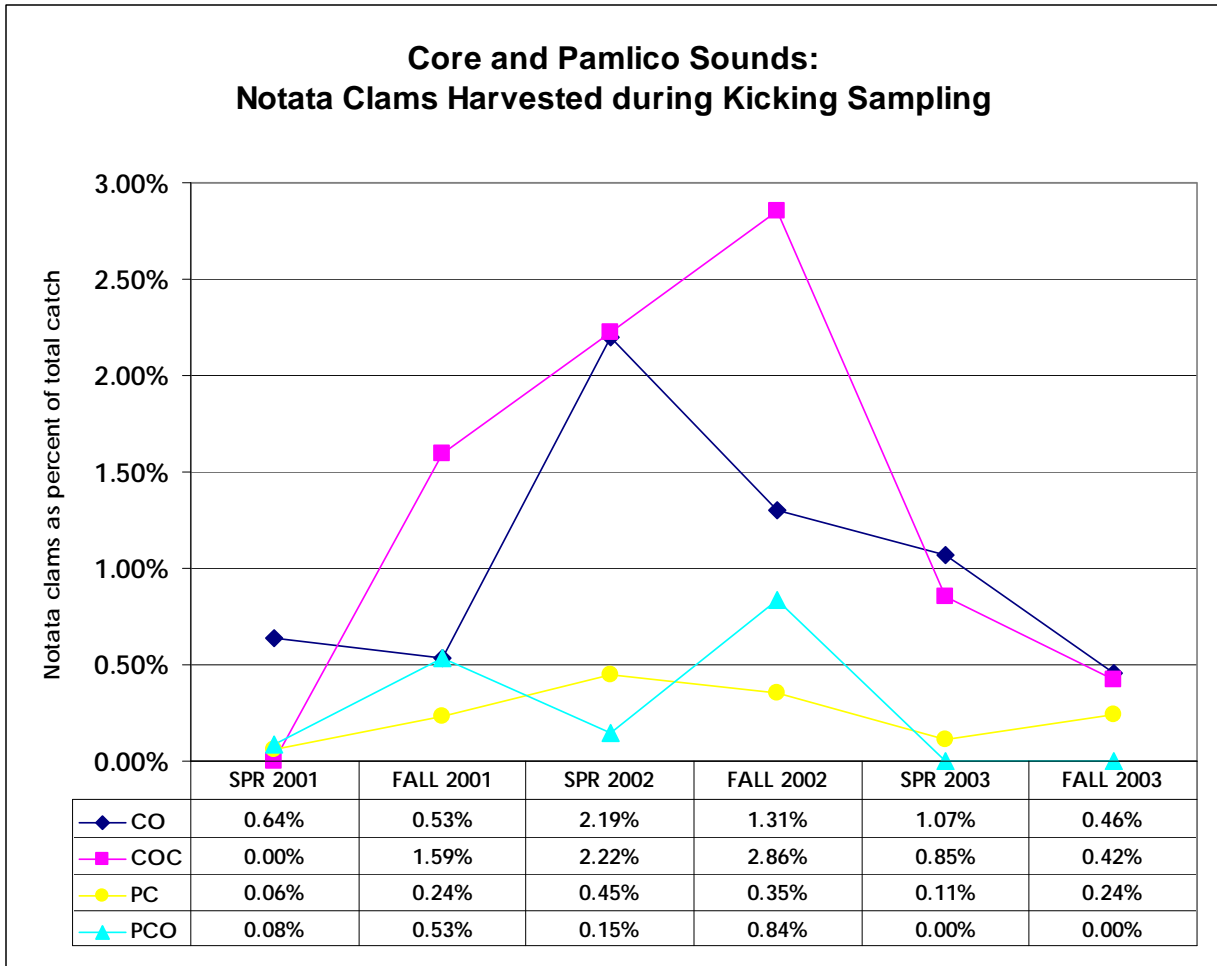
Table 4.2. Overall results combined by treatment of the stone crab-hard clam experiment. The 16 blocks were composed of 64 cages, 16 of each treatment.

Treatment	Overall Results
A	52% of *notata* clams eaten (61% heterozygous,50% homozygous,54% unmarked)
B	59% of wild-type clams eaten
C	43% of total clams eaten (48% wild-type, 38% *notata*)
D	100% clam retrieval, with 8% mortality (63% wild-type, 37% *notata*)

Figure 4.4. Comparison of Treatments A and B. The proportion of clams eaten are plotted versus block number.
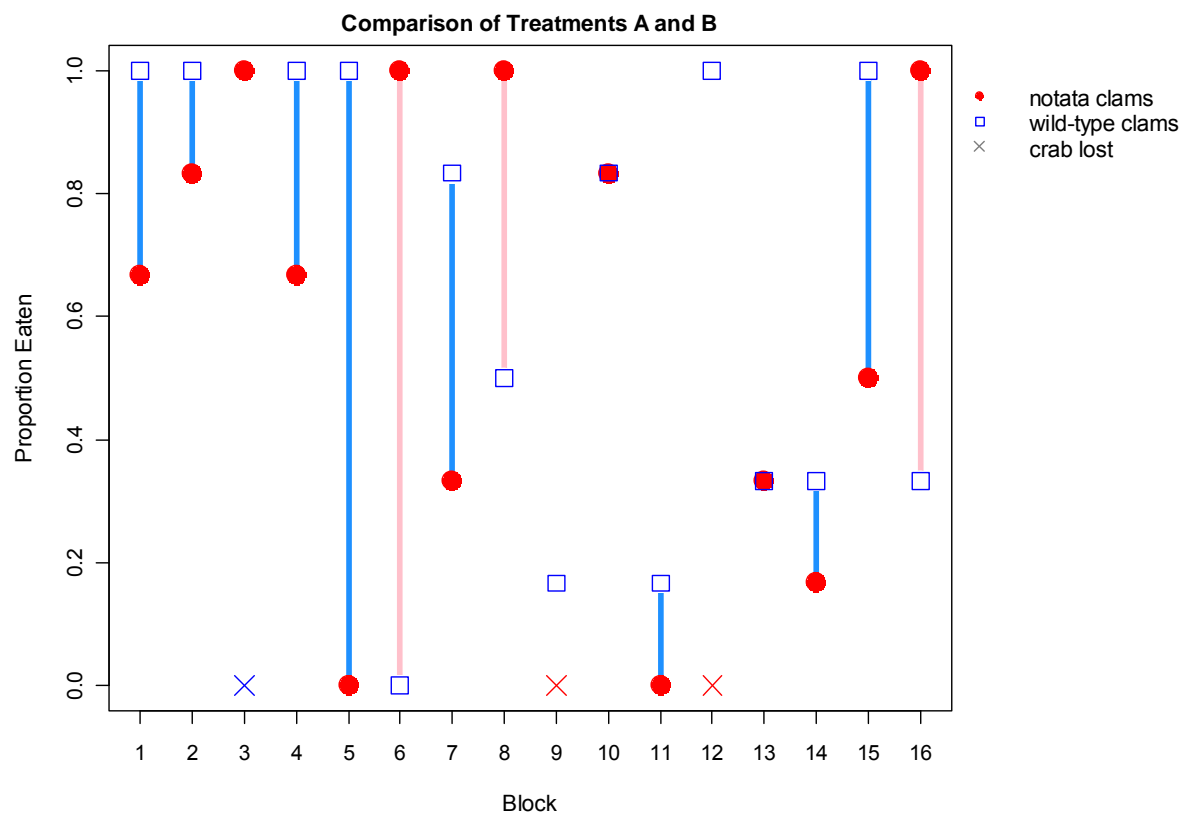
Figure 4.5. Length vs. width relationship for experimental clams. Clam type and mortality are included. Note that the *notata* are generally smaller and less variable than the wild-type clams.

Relationship Between Length, Width and Mortality for Experimental Clams
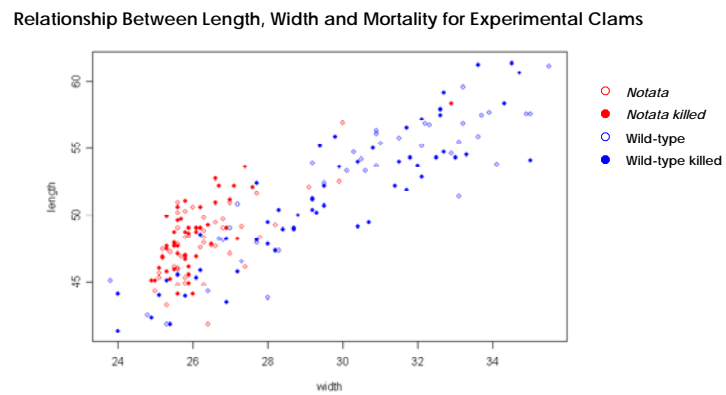
Table 4.3. This is the model comparison for Treatments 1 and 2. *k* is the number of parameters.

model	AIC$_C$	AIC	loglikelihood	*k*
10:width,crab,length,width*length	122.4	118.6	−53.30	6
9:width,crab,length	122.5	119.9	−54.95	5
5:width,crab	125.0	123.3	−57.65	3
3:crab	126.0	125.0	−59.50	3
6:treat,crab	126.3	124.7	−58.35	4
length,crab	126.8	125.1	−58.55	4
8:treat,width,crab	127.9	125.3	−57.65	5
treat,length,crab	129.2	126.6	−58.30	5
1:null	140.8	140.3	−68.15	2
7:treat,width	141.6	139.9	−65.95	4
2:treat	142.4	141.5	−67.75	3
4:width	143.3	142.3	−68.15	3
length	148.8	146.2	−68.10	3
nothing (no random effects)	159.1	159.0	−78.50	1
treat (no random effects)	161.2	160.7	−78.35	2

Table 4.4. Results for Model 9.

Parameter	Estimate	Standard Error	DF	t stat	Pr > |t|	Lower	Upper
intercept	−32.2915	13.1467	15	−2.46	0.027	−60.313	−4.270
width	−1.2929	0.5646	15	−2.29	0.037	−2.496	−0.0895
crab size	0.2436	0.07772	15	3.13	0.007	0.0780	0.409
length	0.9078	0.4479	15	2.03	0.061	−0.0470	1.862
τ^2	4.5251	3.1112	15	1.45	0.166	−2.106	11.156

Table 4.5. Results for Model 10.

Parameter	Estimate	Standard Error	DF	t stat	Pr > |t|	Lower	Upper
intercept	−193.36	93.6811	15	−2.06	0.057	−393.0	6.314
width	4.9415	3.5092	15	1.41	0.180	−2.538	12.421
crab size	0.1854	0.07090	15	2.61	0.020	0.0342	0.336
length	3.9663	1.8244	15	2.17	0.046	0.0777	7.855
width*length	−0.1142	0.06467	15	−1.77	0.098	−0.2521	0.02360
τ^2	4.3203	2.6956	15	1.60	0.130	−1.425	10.0659

LITERATURE CITED

Agardy M. T. 1994. Advances in marine conservation: the role of marine protected areas. Trends in Ecology and Evolution **9**:267-270.

Allison, Gary W., Lubchenco, Jane, Carr,Mark H. 1998. Marine reserves are necessary but not sufficient for marine conservation. Ecological Applications **8**:S79-S92.

Bohnsack J. A. 1993. Marine reserves: they enhance fisheries, reduce conflicts, and protect resources. Oceanus **Fall**:63-71.

Chanley P. E. 1961. Inheritance of shell markings and growth in the hard clam, Venus mercenaria. Proceedings of the National Shellfisheries Association **50**:163-169.

Dugan, Jenifer E., Davis,Gary E. 1993. Applications of marine refugia to coastal fisheries management. Can.J.Fish.Aquat.Sci. **50**:2029-2042.

Hockey, P. A., Branch,G.M. 1994. Conserving marine biodiversity on the African coast: implications of a terrestrial perspective. Aquat.Conserv.Mar.Freshw.Ecosystems **4**:345-362.

Jones, G. P., Milicich, M. J.,et al. 1999. Self-recruitment in a coral reef fish population. Nature **402**:802-804.

Lauck, Tim, Clark, Colin W., Mangel, Marc, Munro,Gordon R. 1998. Implementing the precautionary principle in fisheries management through marine reserves. Ecological Applications **8**:S72-S78.

Peterson, C. H., Duncan, P. B., Summerson, H. C., Safrit,G.W.Jr. 1983. A mark-recapture test of annual periodicity of internal growth band deposition in shells of hard clams, Mercenaria mercenaria, from a population along the southeastern United States. Fishery Bulletin **81**:765-779.

Peterson, Charles H., Summerson, Henry C., Luettich,Richard A.Jr. 1996. Response of bay scallops to spawner transplants: a test of recruitment limitation. Mar.Ecol.Prog.Ser. **132**:93-107.

Roberts C. M. 1995. Rapid build-up of fish biomass in a Caribbean marine reserve. Conservation Biology **9**:815-826.

Russ, Garry R., Alcala,Angel C. 1996a. Do marine reserves export adult fish biomass? Evidence from Apo Island, central Philippines. Mar Ecol Prog Ser **132**:1-9.

Russ, Garry R., Alcala,Angel C. 1996b. Marine reserves: rates and patterns of recovery and decline of large predatory fish. Ecological Applications **6**:947-961.

Swearer, S. E., Caselle,J.E.et al. 1999. Larval retention and recruitment in an island population of a coral-reef fish. Nature **402**:799-802.

CONCLUSIONS

The overexploitation and collapse of fisheries worldwide have demonstrated that conventional fisheries management is inadequate and must be combined with Marine Protected Areas or MPAs (Pauly 2002). The majority of scientific research regarding the effectiveness of MPAs supports their success in restoring or protecting fish populations (Halpern 2003). Although it is biologically ideal to establish a fully protected, permanent marine reserve where no extractive activities are allowed, fishermen are strongly opposed to permanently relinquishing fishing grounds. They are more willing to temporarily surrender areas because they have a specific date when they will be re-opened. Therefore, MPAs that are temporally and/or spatially rotated are a possible compromise if scientific study determines that they work, at least to a certain degree. Additionally, if fishermen are allowed to fish in a re-opened MPA that scientists have determined has successfully restored fish populations, then they have a chance to experience firsthand the benefits of the MPA and will respect its boundaries. Using a North Carolina case study, I have studied if rotating MPAs have the potential to be an effective management strategy.

Declining catches of *M. mercenaria* by clam fishermen or "clam kickers" in Core Sound, Carteret County, NC, resulted in the implementation of a new management strategy by the North Carolina Division of Marine Fisheries

(NCDMF Hard Clam Fishery Management Plan, October 2000). The hard clam

fishery provides income to fishermen when other species such as flounder and

shrimp are scarce. Beginning in the fall 2001 season, a mechanical clam

harvesting or "clam kicking" (a fishing technique used exclusively in NC, Guthrie

et al. 1982) area rotation plan using rotating MPAs was established for a two-

year time period. A portion of the traditionally productive area in Core Sound

was closed and a previously protected area in Pamlico Sound was opened, after

which the original clamming grounds would be restored in fall 2003. I performed

a fishery-independent study investigating the various effects of the plan.

My first study (Chapter 1) evaluated if the rotation of MPAs was successful

in increasing fishery productivity in Core and Pamlico Sounds. I divided my

assessment of the rotation plan into three goals. The first goal was to increase

clam abundance in the closed area and possibly the opened area of Core Sound.

Both components of this goal were met. Because there was a seasonality

pattern in which abundances in the fall samples were always higher than those in

the spring, abundances were compared among each season separately. In the

protected area of Core Sound, clam abundance increased significantly during the

course of the plan in both spring and fall, 3- and 4-fold respectively. In the area

of Core Sound that remained opened, abundance of legal clams significantly

increased by 2-fold in spring and not significantly by 1.5-fold in the fall. Both

areas of Core Sound had the same abundances of legal clams in the beginning

of the study; however, by the end the abundance in the closed area had

significantly increased relative to the opened area, with 2.5 times the abundance of clams.

The second goal was to maintain or, at most, slightly decrease clam abundance in Pamlico Sound. I sampled in the newly opened area (one of the rotating MPAs) and in a control area that is permanently closed. It is not clear if this second goal was met, because the abundances in Pamlico Sound varied considerably more than those in Core Sound. From the beginning to the end of the study, the only statistically significant results were found in spring and they both were decreases: abundances decreased 70% in the newly opened area and decreased 40% in the permanently closed area. The fall results were non-significant: in the opened area, abundances increased by 25% and in the closed area, decreased by 35%.

The third goal was to increase overall productivity of the fishery, measured in clam abundance of Core and Pamlico Sound combined. This goal was achieved. Overall productivity of the study area (all four of the areas sampled) increased significantly by 40% from fall 2001 to fall 2003. These results are more striking when placed in a broader context. Based upon annual averages for 2001, 2002 and 2003, productivity in the study area increased by 70%, compared to productivity of the entire state fishery, which declined by 30%. The decline in catches from wild stock may be greater than 30%, because these data include aquaculture production which may have increased during this time period.

My second study (Chapter 2) assesses the changes that occurred in seagrass populations in Core and Pamlico Sounds during the rotation plan. Seagrass beds create an intricate and dynamic system of food and refuge, providing primary nursery areas for ecologically-important and commercial and recreational fishery and shellfishery species. Hemminga and Duarte (2000) reviewed 24 studies in which virtually all found higher species diversity and abundances of fish, decapods and benthic fauna in seagrass than in nearby unvegetated bottom. Mechanical harvesting practices such as clam kicking that come in contact with the sediment are detrimental to seagrass beds, which is why kicking is banned in seagrass beds in NC (Peterson *et al.* 1987).

I did not expect to find seagrass in opened areas because of the kicking ban. However, I collected it in my kicking gear, so I investigated changes in populations of the 2 seagrass species found in central NC, *Zostera marina* and *Halodule wrightii*, associated with implementation of the rotation plan. Although clam kicking may tear up below-ground plant parts (roots and rhizomes), the impacts on the above-ground portions are hypothesized to be greater because they are subjected to higher exposure to disturbance. After two harvesting seasons of protection from clam kicking, the overall density of *Z. marina* significantly increased in the protected area of Core Sound relative to the opened area. I found that clam kicking does not eliminate *Z. marina* from the habitat, but reduces its overall population density resulting in less seagrass per trawl. There was no change in the presence of *H. wrightii* in the closed area relative to the opened area during the course of the study. *Z. marina* is affected more than *H.*

wrightii because the above-ground biomass of *Z. marina* peaks during the kicking season (mostly winter) and is subject to greater impacts of disturbance, including leaf/flower shear, uprooting and burial, while the below-ground biomass of *H. wrightii* is protected by a layer of sediment, for its peak above-ground biomass does not coincide with kicking. These results may be confounded by NCDMF marking off seagrass in areas to be opened before the kicking seasons; further investigation regarding this concern is necessary.

My third study (Chapter 3) investigates how clam size distribution changed in Core and Pamlico Sounds with the implementation of the rotation plan. Harvesting alters the size distribution of hard clam populations in a way different from that in a typical fishery. In most fisheries, the largest fish are the most valuable and are harvested. Hard clams are unusual in that the middle size classes are harvested because they are the most commercially valuable. The smallest ones are not legal to harvest and the largest ones are worth less.

First, I performed an analysis on the Core Sound dataset. Examining the size distributions over time, the closed and opened area trajectories for measures of central tendency, mean and median, and for most measures of variability, standard deviation (SD) and interquartile range (IQR), were almost parallel to each other. Curiously, one measure of variability, MAD, stood out as an exception to this pattern. The MAD trajectories, while initially parallel, became wildly divergent once the rotation plan was implemented. Although it may appear to be obvious that fishing out the middle should have led to an increase in size variability, that's not exactly what was seen in these statistics. To understand the

conflicting signals that were obtained, a simulation experiment was carried out to

see if the observed pattern could be reproduced: no change in the median or

mean, no or minimal change in the SD and IQR, but a large change in MAD.

Parameters manipulated in the simulation were the initial size distribution of the

population, the range of sizes fished, and the intensity of the fishing pressure.

There was a synergy between an initial bimodal size distribution and the

intensified fishing pressure that was picked up by MAD but not the others.

Because the initial bimodal size distribution was probably a consequence of a

long history of "fishing out the middle", what was seen was some kind of positive

feedback on the MAD statistic due to selective intensified fishing pressure.

One of the two major implications of this analysis was that the particular

combination of a bimodal size distribution and a fishing behavior where the

middle size classes were harvested led to a change in MAD. The result became

more interesting when it was realized that the bimodal size distribution was

probably also a product of fishing pressure. This led to the speculation that when

clammers fish out the middle of a population in which the middle has been

previously fished out, MAD will be most sensitive at detecting this. Although the

hard clam fishery is unusual in that the middle size classes are the most valuable

instead of the larger ones, these results may be applicable to fisheries in which

there are slot limits and the middle sizes are the ones that are legally harvested

(in order to protect the larger, older fish).

The second major implication was that having linked increases in MAD to

increases in fishing intensity, an indicator of the effect the rotation plan had on

Core Sound has been obtained. Both areas were fished initially and it can be assumed that the fishing pressure was roughly the same (as indicated by the parallel trajectories for many of the statistics). Once the rotation plan began, MAD in the closed area decreased. This corresponded to what actually happened because fishing pressure was eliminated as a result of the closure. Being able to detect a change in the clam population by sampling that can be linked back to a management strategy provided support that the random sampling was an accurate portrayal of the population as a whole. With a study area as large as this one (4500 acres), this indicated that the sample actually was random. The more interesting result was that MAD in the opened area increased. If clammers were fishing in Pamlico Sound instead, the opened area in Core would have continued on its pre-rotation MAD trajectory, but MAD dramatically increased. According to this analysis, one of the effects of closing one half of Core to clamming was to intensify the fishing pressure on the remaining half of Core. This was obviously an undesired consequence and confirmed by the trip ticket data in which trips to the opened area of Core increased during the rotation plan relative to beforehand.

An analysis was run on the size distribution of the closed and opened areas of Pamlico Sound. There were 3 conclusions of this analysis. The first was that population size structure in Pamlico showed natural oscillations. The analysis suggests that this was a result of episodic recruitment, such that new size cohorts appear in the population periodically but with gaps during which there was no new recruitment. The second was that the effect of fishing

pressure was to dramatically increase the amplitude of these oscillations. The third was that simulation experiments suggest that the size distribution in the closed area could be largely turned into the size distribution of the opened area simply by adding fishing pressure. Differences still remained suggesting that the two areas differ from each other systematically.

My fourth study (Chapter 4) is not directly related to the clam kicking rotation but addresses another important issue in management of the hard clam fishery in NC. I investigated the function of a large clam lease in southern Core Sound along Core Banks (Huber lease #9201) as a sanctuary for reproducing adults in supplementing the surrounding clam populations. Although there are many leases on the mainland side, this lease is the only one located on the banks side of southern Core Sound. Created in the mid-1990's, the seven-acre clam lease protects great numbers of *M. mercenaria notata*, the hatchery or aquaculture variant of the hard clam that is morphologically and genetically distinct (although it originally was a wild-type variant). When the clams reach market size they are removed from the lease. On the lease, there were 5.5 million clams from 1995 to 1998, 1.0 million clams from 1999 to 2001 and 0.5 million clams in 2002 (Huber pers. comm.).

Presumably the clams spawn and export larvae to surrounding areas. Therefore, I sampled for offspring marked with *notata* on transects centered on the lease site but extended north and south to a maximum distance of 8 km along axes of primary current flow.   I sampled by suction dredge, clam rake and clam kicking. By suction dredge, the small number of recruits that I found overall

207

overall (n=17) makes it difficult to draw any conclusions. In this sample, I found 1 *notata* which was 6% of the sample. In South Carolina, *M. mercenaria notata* specimens comprised between 0.71% and 2.17% of the hard clam populations in eleven locations, so the best estimate of their relative abundance is 1.23% (Eldridge *et al*. 1976). I would have needed to find 2 *notata* clams for this value to be significantly different from the background level. By clam rake, I found 11 *notata* clams overall. The percentages of *notata* in the fall 2001, 2002 and 2003 samples were 0.7, 2.7, and 1.4 respectively. The average of these was 1.6%. I would have needed to find 14 *notata* clams for this value to be significantly different from the background level. The values ranged from 0.00% to 2.86% of the population during kicking sampling. Ten of the eleven highest percentages are found in Core Sound, which are much closer to all the clam leases in southern Core Sound (not only the Huber lease) so it was expected that there would be more *notata* found in these areas if larval export was occurring.

For future analyses for the fourth study, Fisher's method of combining independent probabilities can be used to perform a meta-analysis on these three datasets combined. All three ratios (from suction dredging recruits, raking, and kicking) went in a direction suggesting higher frequencies of *notata* than the putative background frequency of 1.23%, yet none was significantly higher. However, combining the three independent p-values into a single test of the hypothesis will result in more power and perhaps even significance. On the other hand, the estimated augmentation is not as great as 1%, so these leases did not contribute substantially to recruitment outside them.