MANAGEMENT STRATEGY EVALUATION FOR THE ATLANTIC SURFCLAM,

SPISULA SOLIDISSIMA, USING A FISHERIES ECONOMICS MODEL

by

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ABSTRACT

MANAGEMENT STRATEGY EVALUATION FOR THE ATLANTIC SURFCLAM, *SPISULA SOLIDISSIMA*, USING A FISHERIES ECONOMICS MODEL

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The Atlantic surfclam, *Spisula solidissima*, is an economically valuable bivalve harvested along the northeastern United States. The surfclam's range has contracted, and the center of the stock's distribution has shifted north driven by warmer bottom water temperatures. Declining landings per unit effort (LPUE) in the Mid-Atlantic Bight (MAB) is one result. Declining stock abundance and LPUE suggest that overfishing may be occurring off New Jersey. The objective of this project is to perform a management strategy evaluation (MSE) for *Spisula solidissima*. The terminal goal is to identify a preferred management option that promotes enhanced surfclam productivity in the MAB and increased fishery viability as indicated by improvement in performance metrics. The active agents of the MSE model are individual fishing boats with economic and quota constraints influenced by captains' behaviors over a spatially varying population. Management alternatives include two closure rules and three closure durations. Simulations showed that LPUE increased under most alternative strategies, by up to 21%, compared to present-day management. The number of clams per bushel was up to 7% greater under present-day management suggesting that the alternative strategies resulted in the landing of larger clams. Stock biomass increased under most alternate strategies, up to 17%, compared to stock

biomass using present-day management. When incidental mortality increased, the benefits seen under alternative management were enhanced. Benefits of alternative management under reduced abundances remained equivalent or increased in comparison to results with present-day abundance. These outcomes suggest that the preferred management option identified by the MSE approach could be valuable in insulating the stock and commercial fishery from further decline.

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CHAPTER I

INTRODUCTION

The Atlantic surfclam (*Spisula solidissima* [Dillwyn 1817]) is an economically valuable burrowing bivalve common to the sandy bottoms off the northeastern coast of the United States and Canada (Weinberg, 2005). The range of *S. solidissima* prior to the most recent period of global warming from 1999 to present-day spanned the western North Atlantic Ocean continental shelf from Nova Scotia to northern parts of South Carolina at depths of 10 m to 50 m with temperature determining the boundaries (Goldberg and Walker, 1990; Weinberg, 1998; Jacobson and Weinberg 2006; NEFSC, 2013). Surfclams are generally not found in areas where average bottom temperatures exceed 25°C (Cargnelli et al., 1999). Surfclams are relatively sessile planktivorous filter feeders that rarely vacate their burrow unless resuspended by storms, after which they rapidly reburrow (Weinberg, 2005). The life span of *S. solidissima* is up to 31 years with a maximum shell length of 226 mm (Fay et al., 1983; Cargnelli et al., 1999).

The distribution of *S. solidissima* has been shifting towards the north and to deeper waters primarily driven by warmer bottom water temperatures (Cargnelli et al., 1999; Weinberg, 2005; Munroe et al., 2013). Early evidence of this trend is the disappearance of surfclams in Virginia and Maryland state waters between the 1970s and the 1990s (Loesch and Ropes, 1977; Powell, 2003). The continental shelf off the Delmarva Peninsula (DMV) was rich in *S. solidissima* during the early to mid-1990s, but declines in growth rates, maximum size, and tissue weights have accompanied increased mortality in this region, with the ultimate result being the distribution of the stock shifting north to the coast of Long Island, NY, (LI), the expansion of populations on Georges Bank (GBK) (Figure 1), and the movement offshore to deeper waters to evade rising bottom water temperatures (Weinberg, 2005; Munroe et al., 2013; NEFSC, 2013). Based on stock assessment data from the NEFSC (Northeast Fisheries Science Center) and bottom temperature time series obtained through implementation of the Regional Ocean Modeling System for the northwestern Atlantic, episodic warm years have been suggested to cause an increasing frequency of high mortality events in the commercial target resource of older and larger clams (Narváez et al., 2015). In the latter simulation study, thermal stress was found to decrease the *S. solidissima* stock by 2% to 9% on the shelf regions that coincide with a majority of commercial fishing grounds.

During the 1997 to 1999 period, the surfclam population was found to be near carrying capacity throughout most of its range (NEFSC, 2013). However, separate surveys by the National Marine Fisheries Service's (NMFS) Northeast Fisheries Science Center (NEFSC) and the New Jersey Department of Environmental Protection in 2002 revealed a large mortality event after 1999 that eliminated surfclams from the southern region of Delmarva followed by stock declines in both state and federal waters off New Jersey (Powell, 2003; Kim et al., 2004). An additional survey was conducted in 2004 with cooperation from NEFSC, Rutgers University, and the surfclam industry to address concerns about the diminishing range of the fishery's resources (Weinberg et al., 2005). The results of the cooperative survey confirmed the northward and offshore shift in the stock of surfclams. The survey found no significant biomass of surfclams in the southern Virginia (SVA) region and inshore Delmarva (DMV), whereas the northern New Jersey (NJ) populations had the largest biomass of the survey region, and the biomass was found to be shifting into deeper waters (Weinberg et al., 2005; NEFSC, 2013).

Rising bottom water temperatures above approximately 20°C have negative effects on surfclam nutrition and cause physiological constraints on clams living in the southern end of the Mid-Atlantic Bight (Marzec et al., 2010). The surfclam reaches marketable sizes of 120 to 150 mm in shell length within six to seven years depending on the region and the environmental conditions such as food supply and water temperature (Weinberg, 1998; Cargnelli et al., 1999; Weinberg et al., 2002; NEFSC, 2013). Growth rates within the first three to five years have been reported to be similar across the range of the habitat and are positively correlated with distance from shore after the fifth year (Cargnelli et al., 1999). However, as the range for surfclams shifts north due to climate changes, primary productivity is insufficient to support the biomass of the physiologically-impaired (lower filtration rates) clams along the southern and inshore boundary leading to a reduction in growth rate and maximum size (Munroe et al., 2013). Munroe et al. (in press) have shown that maximum size has declined over much of the stock since 1980. Simulation modeling of surfclam population dynamics shows that this outcome can be derived solely from rising temperatures (Munroe et al., 2013; Munroe et al., in press), although a change in food supply would provide the same outcome.

Along the Mid-Atlantic coast, *S. solidissima* has supported a fishery since the 1960's that is valued at millions of dollars annually reaching total revenues of $29 million in 2011 (Weinberg, 1999; Weinberg et al., 2005; NEFSC 2013). The current Fishery Management Plan (FMP) for the surfclam uses an Individual Transferrable Quota (ITQ) system that allocates a resource (i.e. the number of cage landings supported by the surfclam stock) among shareholders (McCay et al., 1995; MAFMC, 2013; NEFSC, 2013). Use of the ITQ system began in 1990 with the addition of Amendment 8 to the original FMP (Weininger, 1998). The FMP recognizes all *S. solidissima* in the Exclusive Economic Zone (EEZ), federal waters from 4.8 to 322 kilometers offshore, as a single stock (MAFMC, 2013). Last year, the New Jersey survey did not catch a market-size surfclam in New Jersey state waters. The decline of this stock is not due to overharvesting. Average fishing mortality rate in the stock south of Hudson Canyon has been higher than the fishing mortality rate over the whole stock and of the northern region from 2002 to 2011; however, this rate is still less than the natural mortality rate (NEFSC, 2013). The fishing mortality rate has historically been less than 25% of the natural mortality rate (NEFSC, 2013); very likely, warmer bottom water temperatures are responsible for the decline in abundance inshore and downcoast, either directly or through the influx of new predators. For example, anecdotal reports of increased cownose ray activity have become increasingly common in recent years in this area, (E.N. Powell, personal commun.).

For the last thirty years, most of the commercial landings within the EEZ have been harvested along the coast of New Jersey and the Delmarva Peninsula (Weinberg, 1999; NEFSC, 2013). The 2011 assessment of commercial landings of surfclams reports total yields of 20,000 metric tons (mt) of meat, with 18,600 mt originating from federal waters, a decrease from a total yield of 22,519 mt in 2008 (NEFSC, 2013). The federal fishery had peak commercial landings from 1972 to 1975 followed by historic low landings in 1979 after the late 1970s anoxic event, but then recovered and has been relatively stable through the late 1990s (Falkowski et al., 1980; NEFSC, 2013). Landings within the last decade show a decline coincident with the latest phase of range contraction that began off Delmarva between 1999 and 2002. The reopening of George's Bank in 2010 allowed for some relief of fishing pressure in other regions, but landings in the southern regions (i.e. all regions excluding George's Bank) have been in steady decline since 2008 (Figure 2) (Cargnelli et al., 1999; Weinberg, 2005; NEFSC, 2013).

The management of *S. solidissima* and the industry it supports relies on data from surveys, landings, and modeling of population trends to set total annual quotas used in management (Normant, 2010; NEFSC, 2013). Since 1982, the NMFS has conducted resource assessment surveys every two to three years (Weinberg, 2005). Information from NMFS surveys over the last twenty years in combination with surveys conducted by other sources (e.g. the New Jersey Department of Environmental Protection) suggests a temperature-driven shift in stock biomass that transfers fishing pressure to areas that provide higher landings per unit effort (LPUE) (Powell, 2003; Kim et al., 2004; Munroe et al., 2013; NEFSC, 2013). The terms “overfished” and “overfishing” relate to the how much of the stock biomass can be harvested without causing long-term stock declines (NEFSC, 2013). According to the latest stock assessment, *S. solidissima* is not overfished, and overfishing is unlikely to occur in the next five to seven years (NEFSC, 2013). However, low LPUE and declining stock abundance has led to the closure of a once thriving clam fishery in southern areas of the range and has contributed to regional overfishing off New Jersey (Powell, 2003; Weinberg et al., 2005; NEFSC, 2013). Georges Bank (GBK), the northernmost region of the EEZ, closed in 1990 due to the risk of harvesting clams contaminated with paralytic shellfish poison (Jacobson and Weinberg, 2006). GBK reopened in 2013 to provide additional resources to the fishery (NOAA, 2012). Most vessels in the commercial fleet cannot operate in this area due to constraints involving distance from the area to processing plants, however. Thus, heavy fishing pressure remains offshore New Jersey and has driven a desire to enhance production in the New Jersey portion of the stock (Figure 2).

Area management has proven to be a useful tool for recovering a fishery, particularly for sessile species (Powell et al., 2008; Cooley et al., 2015). Successful implementations include the sea scallop (*Placopecten magellanicus*) fishery in the Mid-Atlantic and New England region (Cooley et al., 2015) and the oyster fishery in Delaware Bay (Powell et al., 2008). One method of examining the risks and benefits associated with a management plan is by conducting a management strategy evaluation (MSE). A MSE is a technique to integrate commercial knowledge and stakeholder concerns, such as commercial fishing behaviors and trends, with biological knowledge, such as population dynamics estimated by surveys and assessments, to derive information that supports fisheries managers' regulatory decisions (Smith, 1994). A MSE is a quantitative tool used to evaluate a range of possible management procedures, by comparison of performance statistics or metrics (Butterworth and Punt 1999; Martell et al., 2013). Butterworth et al. (1997) describe management procedures as "a set of rules which utilize pre-specified data to provide recommendations for management actions". Performance metrics should be chosen carefully, preferably in collaboration with the stakeholders of the fishery to ensure clear and easy interpretation of simulation results (Francis and Shotton, 1997). MSE has been used to contrast the performance of fishery management alternatives of fisheries including the Pacific Halibut (Martell et al., 2013) and U.S. southeastern king mackerel (Miller et al., 2010).

The objectives of this project are to evaluate a range of management strategies to identify options that may improve the Atlantic surfclam stock in the Mid-Atlantic Bight, thereby enhancing the economic opportunities of the surfclam commercial fishery. The focus of this MSE is on area management options due to the successful track record of regional closures in other bivalve fisheries. Following the specification of management options, a series of simulations will be conducted and evaluated based on performance metrics for varying stock abundance, distribution, and commercial procedures, including fishing behaviors.

The inclusion of fishing behavior is critical because captains will respond to new management measures, and this response will in part determine the degree of success of those measures after implementation (Gillis et al., 1995; Mackinson et al., 1997; Dorn, 2001; Millischer and Gausel, 2006). Statistical analysis of the simulation results will include pairwise comparisons of performance metrics pertinent to proliferation of the species and the sustainability of the fishery identified in collaboration with leaders of the commercial fishery. Preferred options will be identified as management strategies that provide a statistically significant improvement in performance metrics in comparison to present-day management.

CHAPTER II

METHODS

Model Description

The main tool of this study is an individual-based model of a spatially and temporally variable population of *S. solidissima* (Figure 3) (Powell et al., 2015). Powell et al. (2015) provide a detailed description of the model, including parameterization of surfclam population dynamics, processer constraints and vessel fishing dynamics, management and regulatory constraints, and survey protocols. The primary model is written in Fortran 90 with post-processing in MatLab and statistical analysis performed in SAS. A commercial fleet of vessels harvests the *S. solidissima* stock. Each vessel is assigned to one of three ports (Figure 4). The fishing vessels are the active agents in the model and are associated with ports from which they must always leave and return. The characteristics of the fleet simulated in the model, including their operational constraints, are based on data collected from the present-day commercial fleet. Operational constraints imposed by or on the vessel include the maximum allowed fishing time, vessel speed, and the executed harvest quota (i.e. the quota set for the year by managers). During a simulation, vessels harvest surfclams based on captains' decisions and operational constraints. Fishing locations are selected based on the captain's knowledge of the ten-minute square (TMS) in which the vessel can be filled in the shortest time with the least total distance traveled (i.e. the closest TMS with the greatest catch rate).

The spatial domain of the model divides the range of *S. solidissima* in the Mid-Atlantic Bight into TMSs. Each TMS has an idiosyncratic clam density. The TMS is chosen as the area of interest because the resolution of logbook data used for management measures is the TMS (NEFSC, 2013). The study area encompasses the majority of the fishable region and is located on the continental shelf off Long Island, southern New Jersey, and the Delmarva Peninsula excluding southern New England and Georges Bank. The latter two regions are excluded because concerns about local overharvesting have not been raised either due to the high abundance relative to fishing pressure (Georges Bank) or to low exploitation due to historically limited resource availability (southern New England). For simplicity in presentation of results, the spatial domain of the study area is rotated counterclockwise with inconsequential effects on the model processes (Powell et al., 2015; Figure 4). A domain mask is imposed to exclude squares where no clams are found based on habitat or physiological constraints (i.e. depth and bottom water temperatures). Ports for this study are the present-day active ports for surfclam landings and are located from north to south at Oceanside, NY, Atlantic City, NJ, and Point Pleasant, NJ. A single vessel still fishing out of Ocean City, Maryland, is excluded. This vessel is assigned to the primary port supporting that owner's fleet, Atlantic City, based on the likelihood that Ocean City will be fully abandoned as a port by the surfclam industry in the near future (E.N. Powell, personal commun.).

The distribution of adult surfclams can range from loose aggregations to dense beds (Fay et al., 1983; Ropes, 1980). The initial distribution of the stock created by the model ranges from high to low density. The patchiness of the distribution is based on the total clam density distributed to each TMS using a negative binomial random distribution. The patchiness of the distribution is controlled by changing the variance in the abundance of clams in each TMS to the mean abundance. Patchiness of the distribution is included in this study as a sensitivity analysis with a range that is typical of bivalve populations and consistent with federal survey data. The patchiness of the distribution has no effect on fertilization efficiency in this study due to insufficient data; thus, population densities are assumed not to limit fertilization efficiency. Recruitment is an annual event. The recruitment rate is manipulated by imposing varying rates of larval mortality, which results in varying levels of post-settlement abundance.

A burn-in time of 100 years simulates the unfished population so that equilibrium with the specified population characteristics (e.g., mortality rate) is reached. At year 100, the stock is at carrying capacity, and characterized by a locally patchy distribution with regional characteristics consistent with the latitudinal and offshore temperature gradients. An additional 25 years are simulated to permit the fishery to reduce the stock below carrying capacity (e.g., to present-day abundance for present-day simulations) and to permit captains' memories to evolve. Captains' memories retain information about previous fishing trips such as TMSs fished and catch from that TMS. These memories are then used in making decisions about where to fish in future trips. An additional 76 years are simulated to produce fishery and population data under alternative management. During this 76-yr period, surfclam population and commercial fishing data are collected for each of the years. These data are used for statistical comparisons of performance metrics. Each simulation takes a total of time of 201 years.

Hypotheses

H_1: Area management will not enhance the *Spisula solidissima* population in the Mid-Atlantic Bight.

H_2: Area management will not provide additional economic opportunities for the commercial *Spisula solidissima* fishery in the Mid-Atlantic Bight.

Methods for Hypothesis Testing

The essential elements of a management strategy evaluation include management objectives, performance metrics, and management options (Smith, 1994). Management objectives and performance metrics used to evaluate the alternative management procedures were identified in collaboration with the surfclam industry by a series of interviews and meetings. The primary management objectives are to insulate the *S. solidissima* stock and commercial yield of the resource from further decline. The performance metrics include clam stock density (i.e. density of clams that are equal to or greater than 120 mm in shell length per square meter), landings per unit effort (LPUE), the amount of unused quota, total annual yield, the number of clams per bushel, the number of TMSs fished to reach the annual quota, and the total distance traveled per fishing trip (measured in kilometers). LPUE is the number of bushels fished per hour. The amount of unused quota is measured in cages (one cage = 32 bushels).

Yield is the meat wet weight in pounds per bushel. Yield is the most difficult metric to simulate. The difference between shell size and meat volume is not tracked within the model. The model uses a condition index (i.e. meat weight at a given shell size) that is varied regionally based on historic seasonal trends in yield provided by the industry (Powell et al., 2015). However, local variations in yield that may accrue, for example, from local variations in temperature, are not simulated. Thus, yield is included here but not to the resolution of more sophisticated models such as the model used in Narváez et al. (2015). The management options include a range of closure locations and durations discussed later in this section.

Varying states of nature can cause marked differences in the density and disposition of a stock and influence success of management alternatives. In this study, both variations in recruitment and stock distribution are simulated in increasing degrees of abundance and dispersal. Stock abundance is modified in the model by varying the recruitment rate using small, medium, and large recruitment events, with each level producing a stock abundance that is double the previous one (i.e. small recruitment events produce half of the stock abundance of medium recruitment events and medium events produce half the level of large recruitment events). The medium-sized recruitment event scenario produces present-day abundance. The higher level is indicative of 1990s abundances prior to the most recent phase of range shifting. The lower level sets a stock abundance that is just above the level that would trigger quota restrictions based on present-day biological reference points used for management of the fishery. Stock distribution is described by three degrees of increasing patchiness of recruitment obtained by increasing the ratio of the variance in recruitment among TMSs to the mean for the entire population with each degree being a variance-to-mean ratio approximately twice the value of the previous one (e.g., medium patchiness has a variance-to-mean ratio that is approximately twice that of low patchiness).

Incidental mortality of clams that remain on the sea floor after dredging is investigated by setting incidental mortality to 0% and 20% of the clams intercepted by the dredge but not caught in the dredge. The assumption that is currently made by NMFS is that incidental mortality is approximately 12% (NEFSC, 2013). For each of the states of nature and for the two levels of incidental mortality, simulations are performed using present-day management for comparison to area management options. The cases representing present-day management are termed base cases hereafter.

Incorporation and manipulation of various commercial procedures allow for an investigation of the fishery and the plausible options for enhancement of economic opportunities. Captain behavioral types, closure durations, closure locations, and age at harvest (i.e. age of the clam when it reaches a defined market size) have all been identified as pertinent commercial physiognomies when considering management strategies. The facets of commercial procedures are rooted in interviews conducted with commercial leaders including processing plant managers and vessel captains.

One of three captain types is included in each simulation. Captain behaviors are exclusive to each captain type (i.e. captains who search do not use survey data). Standard captains do not search for new fishing grounds and do not use survey data. Survey captains update their knowledge every three years with data from NMFS population surveys. The use of NMFS survey data by captains has been found to improve performance in simulation studies (Powell et al., 2015). Confident captains spend 20% of fishing time searching for new more prosperous fishing grounds. Searching behaviors have produced similar positive changes in performance as using survey data (Powell et al., 2015). The captain behaviors serve as replicates for each level of population abundance and degree of patchiness in recruitment (Table 1). Each individual simulation has a defined abundance level, degree of stock patchiness, and captain type. Twenty-seven simulations, one simulation for each combination of captain type and stock characteristics, constitute one set of cases. Sets of cases are repeated for each definition of a small clam and closure duration. This results in four sets of cases per closure duration (one set for each definition of a small clam) and 16 sets per closure location rule (Figure 5). The structure of the base case is composed of the same states of nature (abundance and distribution) and captain behaviors as the alternative management cases, excluding area closures.

Hypotheses are tested by comparing performance metrics from sets of cases under present-day and alternative management (Figure 6). Management alternatives consist of closures of one TMS per year during the 76 simulated fishing years. The ITQ system is still used for the 76 simulated fishing years. The management alternatives simulate the addition of area closures to the current management plan. Area closure locations are based on one of the two rules and affect the TMS in each of the 76 fishing years with the largest rule-specified value. If Rule 1 is executed, the TMS with the highest ratio of small clams to market-size clams that is greater than 0.05 is closed each year. Rule 1 focuses on the importance of the proportional presence of small clams. If Rule 2 is imposed, the TMS with the largest density of small clams per m^2 that is greater than 0.05 is closed each year. Rule 2 considers the population of small clams as a whole over an area. Closure durations of three-, four-, five-, and seven-years (of each TMS closed in a year) are compared to no closures. This results in three, four, five, or seven TMSs being closed on average during each of the simulated years. The fishable area in the model domain (Figure 4) consists of roughly 52 TMSs. The fishable area represents the TMSs where vessels currently or historically harvest clams. Each TMS has independent biology from surrounding TMSs. The closure durations would result in 6%, 8%, 10%, and 14%, respectively, of the fishable area being closed at any one point in time after the maximum number of TMSs were closed (e.g. for the five year closure duration, five TMSs (10% of the fished area) would be closed at a given time). The four-year duration was examined only for performance metrics where clarification of effect was needed between the 3- and 5-year closure durations.

The success of both of the area management rules varies depending on the definition of a small clam. The definition of a small clam that is implemented in the simulations is a value that depends on the time required for a clam to grow to market size (120 mm, NEFSC 2013). The specified size depends on growth rate, which is variable across the domain. This variation allows for clams to grow faster in some regions than in others depending on water temperature. A range of growth years to reach harvest size is investigated in this study from two to five years. A small clam is defined based on the size (shell length) a clam would be to become market-sized (120 mm) in a defined period of time. For convenience, an average of these sizes is used to identify growth years in presentation of simulation results. These averages are 104 mm, 93 mm, 80 mm, and 64 mm for 2, 3, 4, and 5 growth years, respectively. Investigation of a range of definitions not only allows for a variable growth rate to be examined, but also a variable definition of a small clam by fishery managers.

Statistical Evaluation of Alternative Management Strategies

The evaluation of alternative management procedures for both the enhancement of the *S. solidissima* stock and the economics of the industry is based on statistical analysis of performance metrics. The performance metrics are rooted in interviews with commercial leaders and vessel captains to ensure clarity. The performance metrics chosen by the commercial leaders are important in that they provide metrics that allow commercial leaders to evaluate the results of each management procedure based on their business model. The metrics used are the density of the marketable clam stock (clams/m^2), the amount of unused quota (cages), the number of clams per bushel (clam bu^{-1}), yield (lb bu^{-1}), LPUE (bu h^{-1}), the number of TMSs fished in a year, and the distance traveled per fishing trip (NM). The population is evaluated by the number of clams in the entire population, the amount of unused quota, yield, and the number of clams per bushel. The effect of area management on the commercial industry is evaluated by LPUE, the number of TMSs fished, and the total distance traveled per fishing trip.

The statistical approach used to evaluate the management strategies is the non-parametric Wilcoxon signed-rank test (Conover, 1980). This test uses the difference in metric values between two outcomes, in this case the difference between the base case and the otherwise equivalent simulation under alternative management (e.g. Rule 1, Rule 2, closure durations, and small clam definitions (= time to market size)) (α = 0.05). Each comparison was based on 76 years of simulated time, with one difference calculated for each year; thus, a single Wilcoxon test was based on n = 76 (Figure 7). As each year was different from each succeeding or preceding year because a TMS was opened and closed each year, each year represented a unique comparison between the area management and otherwise equivalent base case. Each comparison between present-day and alternative management is based on nine sets of simulations with present-day abundance and varying captain's behavior and patchiness of recruitment (Table 1). Thus, nine Wilcoxon tests were conducted for each set. The likelihood of a significant number of significant outcomes from these nine tests was evaluated by an exact binomial test (α = 0.05) (Conover, 1980). Any case where more than one of the nine sets differed significantly was more than expected by chance at α = 0.05.

Performance metrics were evaluated by the proportion of simulations that resulted in an increased performance metric in comparison to the base case with the same composition and the amount of increase seen in those significant simulations. Management strategies that result in a large proportion of simulations that show improvement in comparison to the base case (even if the proportional increase is small) are preferable because that given scenario would be more likely to result in improvements than a scenario with few simulations showing improvement. Simulations with larger proportions of increase in performance metrics in comparison to the base case and other alternative management strategies are preferable. In addition to comparison between the sets of alternative management and base cases, a second series of comparisons was conducted between alternative strategies consisting of comparisons of the proportion of simulations with improved performance metrics and also the proportion of increase; these offer additional insight as to which management procedures offer the most benefit.

CHAPTER III

RESULTS

The Effect of Closure Location on Performance Metrics

Closure Location Based on Rule 1: The Ratio of Small Clams to Market-Sized Clams

Stock density. A greater percentage of simulations show significant stock density increases when the definition of a small clam was 93 mm or 80 mm (Table 2), which is representative of clams that will reach market sizes (120 mm) in 3 and 4 years respectively. As the duration of the closure increased from three to seven years, the average percentage of simulations with significant increases in stock density under area management across all definitions of a small clam increases. The 3-year closure duration resulted in an average increase in stock density of 5% (Figure 8); 42% (Table 2) of simulations showed a significant increase of stock density compared to present-day management. Both the 4-year and 5-year closure durations resulted in an average 4% increase in stock density over all definitions of a small clam (Figure 8); 44% of 4-year and 5-year closure duration simulations showed a significant increase in stock density. The greater average percent of simulations that showed a significant stock density increase compared to present-day management is seen with the 5-year closure duration (33-67%; average 47%, Table 2). The 7-year closure duration resulted in a 7% average increase in stock density (Figure 8), the largest average stock density increase across all definitions of a small clam. The 7-year closure showed a significant increase in stock density in an average of 44% (range of 33-56%;

Table 2) of the simulations in comparison to present-day management. When the imposed incidental mortality on clams not retained by the dredge is increased from 0% to 20%, a higher percentage of simulations show significantly increased stock density and the degree of increase in stock density was also larger (Table 3).

Amount of unused quota. The average amount of unused quota over all definitions of a small clam increases as the duration of the closure is increased. The 3-year and 5-year closure durations resulted in an average of 2% of the quota remaining unused (Figure 8), with only 14% (Table 2) of simulations showing a significant increase compared to present-day management. The 4-year closure duration was not investigated for this metric because of the lack of difference between the 3- and 5-year closure durations and the negligible amounts of increase over all simulations and durations (Figure 8). The 7-year closure duration resulted in the largest average increase in the amount of unused quota of 3% (Figure 8). The 7-year closure consistently resulted in more unused quota than the other closure durations and had significantly more unused quota in an average of 41% (range 33-44%; Table 2) of the simulations in comparison to present-day management. Increasing the imposed incidental mortality of clams that remain after dredging resulted in a larger percentage of simulations having more unused quota under present-day management (Table 3). Percent increases were still diminutive for simulations using present-day or alternative management (Table 3).

Yield. Yield was not increased by more than 1% for any closure duration at any definition of a small clam (Figure 8). Although increasing imposed mortality caused more simulations to have higher yield than present-day management, percent increases were still less than 1%. Yield, as mentioned in the methods section, is the most difficult performance metric to model accurately and has the lowest resolution due to the fact that the model used in this study does not record differences in the shell size to meat weight relationship. A small effect in the proportion of increase in yield is to be expected owing to the low resolution in yield changes within each clam. A better estimation of yield can be deduced from the number of clams per bushel.

Number of clams per bushel. As the closure duration increases from three to seven years, fewer clams are required to fill a bushel. Having fewer clams per bushel suggests that larger clams are landed under alternative management and that as the duration of the closure increases, the size of landed clams increases. The percent of simulations that showed significantly more clams per bushel under present-day management reaches 100% (Table 2) for all 5-year and 7-year closure durations. The number of clams per bushel was an average of 4% greater under present-day management than using the 7-year closure duration (Figure 8). Although an average of 34% of simulations using the 4-year closure duration have more clams per bushel when compared to the 5-year duration, only 33% of simulations were significantly different between the 4- and 5-year durations. The increased clam size as the duration of the closure increases was not affected by an increase of imposed incidental mortality (Table 3).

Landings per Unit Effort. As the size definition of a small clam decreases, higher percentages of simulations recorded significant LPUE increases under the 5- and 7-year closure durations in comparison to the base case. The proportion of clams in the stock defined as small increases as the size definition of a small clam decreases. For example, as the definition of a small clam changes from 93 mm to 80 mm, more clams in the population are defined as small because the clams between 92 mm and 80 mm are now added to the number of clams deemed to be small. LPUE declines when the size definition increases because TMSs with the highest clam density, which are now dominated by small clams, are being closed based on the location option rule (close TMS with largest ratio of small clams to market-sized clams).

All of the examined closure durations resulted in average increases of 6% in LPUE (Figure 9). The 3-year closure duration resulted in 61% (Table 4) of simulations showing a significant increase in LPUE compared to present-day management. The 5-year closure duration has the highest average percent of simulations that showed a significant LPUE increase compared to present-day management (range 33-89%, average 64%, Table 4). The 7-year closure has the lowest average percent of simulations showing a significant increase in LPUE in comparison to present-day management (range 33-56%, average 44%, Table 4). When additional incidental mortality is imposed, the effect of alternative management in increasing the LPUE is enhanced (Table 3). The 5-year closure duration resulted in an average 15% increase in LPUE, and 75% of simulations had significantly increased LPUE in comparison to present-day management (Table 3).

Number of Ten-Minute Squares Fished. The number of TMSs fished during a year increases as the closure duration decreases (Figure 9). This is because captains are targeting TMSs that recently opened after being closed for some duration of years. A TMS that has been closed for a longer duration will result in the landing of larger clams and have a higher stock density, thus LPUE will be higher leading to the vessels targeting these TMSs; consequently, fewer TMSs are visited to fill quotas. Increasing the incidental mortality imposed on clams that remain after dredging results in a larger percent of simulations with significantly fewer TMSs fished during the year. Increased mortality also causes larger margins of percent decreases of TMSs visited under alternative management.

Distance traveled per fishing trip. The 3-year closure duration resulted in an average of 24% (range 11-33%, Table 4) of simulations where the distance traveled to the fishing ground was increased significantly, an average increase in distance over all simulations of 3% (Figure 9). Due to the negligible difference in percent increases between the 3-year and 5-year closure durations, a 4-year duration was not investigated. The 5-year closure duration also resulted in an average increase in distance traveled of 3% (Figure 9), but 47% (range 44-56%, Table 4) of simulations showed significantly increased distance traveled under area management. The 7-year closure duration demonstrated the highest percent of cases having significantly greater distances traveled (average 58%,

Table 4). Accordingly, the 7-year closure duration also resulted in the largest average percent increase in distance traveled (8%, Figure 8). The increased distance as closure duration increases means that some of the TMSs that are closed are close to the ports and would otherwise be targeted by the fishery; thus a longer closure duration results in more TMSs close to the ports being closed at a given time. As a consequence, larger distances must be traveled to reach fishable TMSs. The average percent increase in distance traveled was 4% (Figure 9) for all closure durations. When incidental mortality imposed on clams that remain after dredging was increased, the percent of cases that had significantly greater distances traveled under area management decreased (Table 3).

Closure Location Based on Rule 2: The Number of Small Clams per m^2

Stock density. The 3-year closure duration resulted in an average increase of 4% in stock density (Figure 10), but an average of only 36% (range 33-44%; Table 5) of simulations showed significant increase in stock density compared to present-day management. The 4-year duration resulted in an average increase of 5% in stock density over all definitions of a small clam (Figure 10). An average of 44% of the 4-year and 5-year closure duration simulations were significantly different from each other in regards to reporting stock density increases in comparison to the base case. The 5-year duration resulted in an average increase in stock density of 4% (Figure 10). The 5-year closure duration also had the highest average percent of simulations that showed a significant stock density increase compared to present-day management (range 33-67%, average

50%; Table 5). The 7-year closure duration resulted in a 5% average increase in stock density (Figure 10). On average, the 7-year closure showed significant increases in stock density in only 39% (range 0-56%; Table 5) of the simulations in comparison to present-day management. An increase in incidental mortality enhances the effect of alternative management (Table 6) resulting in average stock density increases of 7% to 8% over the range of closure durations and definitions of a small clam.

Amount of unused quota. Present-day management resulted in a significantly higher percent of simulations having more unused quota when compared to any alternative management strategy (Table 5). As the duration of the closure increased, the amount of unused quota under area management increased (Table 7), and the tendency for present-day management to produce higher levels of unused quota generally decreased. The larger amount of unused quota seen when using longer closure durations could be attributed to more TMSs with the highest clam densities being closed as the closure duration increases. The 3-year and 5-year closure durations resulted in an average of 5% (range 0-11%, Table 5) of simulations having significantly more unused quota than present-day management with 3% and 2% increases in unused quota respectively (Figure 10). The 4-year duration was not investigated for this metric due to the low percent of simulations with significantly more unused quota seen with the 3- and 5-year durations. The 7-year closure duration resulted in the largest percent of simulations having significantly more unused quota when compared to present-day management (average 24%, range 11-33%, Table 5).

The percent increase of unused quota is 3% (Figure 10). To put this value into perspective, if the quota was 25,000 cages then 750 cages would remain unharvested if 3% of the quota was unused. Increasing the imposed mortality of clams that remain after dredging resulted in more simulations having significantly more unused quota under alternative management (Table 6). The percent of increase in unused quota has a maximum average percent increase of 3% using the 7-year closure duration.

Yield. At any definition of a small clam, yield was not increased by more than 1% for any closure duration with or without additional imposed mortality on clams that remain after dredging (Figure 10). Increasing imposed mortality caused more simulations to have higher yield than present-day management (Table 6), but percent increases were still less than 1%. As mentioned earlier, yield is the weakest performance metric due to the difficulty in modeling the metric accurately.

Number of clams per bushel. As the closure duration increases, the catch contains fewer clams per bushel; however, this effect did not vary with a change in the definition of a small clam. Fewer clams being required to fill a bushel suggests that larger clams are landed under alternative management as the closure duration increases. The percent of simulations that showed significantly more clams per bushel under present-day management reached a maximum average of 97% (range 89-100%; Table 5) for 7-year closure durations. Using the 7-year duration, the number of clams per bushel was increased by a maximum average of 3% (Figure 10). The trend of fewer clams per bushel was muted by an increase in incidental mortality. Fewer simulations had significantly more clams per bushel under present-day management, and the percent increase in clams per bushel was a maximum average of 4% using the 7-year closure duration.

Landings per Unit Effort. All of the examined closure durations resulted in average increases of 8% in LPUE (Figure 11). The 3-year closure duration resulted in an increase in LPUE in an average 64% (range 56-89%; Table 8) of simulations when compared to present-day management. The 4- and 5-year closure durations showed significantly enhanced LPUE in an average of 56% of simulations. Of the simulations that were significantly different, the two durations resulted in an equivalent percent of simulations with increased LPUE. The 5-year closure duration resulted in significant increases in LPUE in an average of 64% (range 44-78%, Table 8) of simulations when compared to present-day management. The 7-year duration resulted in the least number of simulations having significantly increased LPUE (average 42%, range 22-67% Table 8). The longest closure having the least amount of simulations with significantly improved LPUE might be attributed to the locations of closure. A closure based on the number of small clams per m^2 might result in closure of some TMSs with the most total clams. As the closure duration increases, more TMSs are closed at a time. With the 7-year closure duration, more of the TMSs with high clam densities might be closed, thus causing a lower average LPUE. Increased incidental mortality resulted in fewer simulations having significantly increased LPUE (Table 6). However, of the simulations where LPUE was significantly enhanced by alternative management, the average proportion of increase in LPUE was improved. The 5-year duration showed the most improvement with LPUE increased by an average of 12% (compared to 8% without additional mortality).

Number of Ten-Minute Squares fished. As the duration of the closure increases, the percent of simulations with significantly more TMSs fished during the year decreases. However, the average percent of increase in TMSs fished under present-day management and over all alternative management strategies is only 3% and 4% respectively (Figure 11). The high percent of simulations that showed no significant difference between present-day and any closure duration (66%, 75%, and 59% for the 3-, 5-, and 7-year durations, Table 8) accompanied by the small percent changes suggest little effect of any alternative management strategy in changing the number of TMSs visited during fishing under the closure location choice based on the density of small clams. The 4-year closure duration was not investigated for this metric for this reason. As imposed incidental mortality is increased, slightly fewer TMSs are visited as the closure duration increases (Table 6). An increase is seen in the percent of cases where significantly fewer TMSs are visited using alternative management; however, the average percent increases of TMSs visited under present-day or alternative management are still 5% or less (Figure 10).

Distance traveled per fishing trip. The distance traveled during fishing is increased significantly in 94% of simulations for the 3-year closure duration and in 90% of simulations for the 5- and 7-year closure durations (Table 8). The average percent increase for each of the closure durations is only 5% (Figure 11). The low percent of changes for the 3-, 5-, and 7-year durations suggests that little change is to be expected under the 4-year closure duration. An increase in incidental mortality resulted in a lower percent of simulations with increased distance traveled during fishing (averages of 41%, 61%, and 64% for the 3-, 5-, and 7-year durations; Table 6). The percent of increase was less than 4% for all durations.

The Effect of Abundance Changes on Performance Metrics

All previous results are from simulations that represent present-day stock abundance. Performance metrics of simulations with higher and lower abundances were also examined. Based on the improvement of performance metrics in comparison to the base case and to closure location Rule 2, Rule 1 is the preferred closure location option (Table 10). The largest effects of alternative management under the preferred closure location rule (Rule 1) are seen in stock abundance, LPUE, and the amount of unused quota when abundance is decreased. As abundance decreases, the percent of simulations that report a higher stock density in comparison to the base case increases (Figure 12). The percent of cases with increased LPUE is lowest in comparison to the base case when abundance is low (Figure 13); however, the percent of simulations with increased LPUE at low levels of abundance using the 5-year closure duration is comparable to present abundance percentages of the same closure duration. The percent of simulations with significantly more unused quota using area management increases as the abundance is decreased (Figure 14). At low abundance, from 78% to 100% of simulations resulted in more TMSs fished under present-day management, which is indicative of captains choosing to fish in the most recently re-opened TMSs. Area management varies outcomes little at high abundance (Figure 14).

CHAPTER IV

INTERPRETATION AND DISCUSSION

Perspective

The goal of this study is to use a MSE to investigate possible options that could offer enhancement to the surfclam stock while improving the fishery without unjustifiably limiting the fishery through undesirable economic impacts.
MSE allows for the evaluation of alternative management options based on performance metrics that are valuable to both stakeholders and fishery managers. Range contraction of *Spisula solidissima* as a result of rising bottom water temperatures in the Mid-Atlantic Bight has important implications not only for the stock but also for the commercial fishery supported by the population in this area. The commercial fishery, which historically spanned as far south as northern Virginia, is now concentrated off the New Jersey shore (Cargnelli et al., 1999; Jacobson and Weinberg, 2006; NEFSC, 2013). Local overfishing is likely to occur as consolidation of fishing pressure in the area increases in order to support the commercial fishery. As fishing pressure increases, the LPUE will likely decline over time if no management plan is set into action to improve the productivity of the stock or transfer additional effort to Georges Bank. Because of the location of processing plants, the transfer of effort to Georges Bank would be extremely expensive and thus represents an economically implausible option.
The ongoing increase in fishing pressure in the study region as a consequence of range contraction is already manifesting a reduced LPUE and an increasing inability to catch the allocated quota. Response to these declines by the fishery is

a critical need. The need to protect and improve the condition of the stock while allowing the continued support to the fishery is also a major problem facing management. Area management has proven to be a useful tool to address this type of problem in other shellfish fisheries.

Although the MSE model (SEFES) captures the essential components of a highly variable system (i.e. the surfclam population and fishery), some limitations are worth considering. For example, the lack of knowledge about incidental surfclam mortality as a result of dredging procedures requires an assumption concerning the degree of its importance. Simulations were conducted for 0% and 20% incidental mortality of the clams not retained by the dredge with the upper value chosen based on no *a priori* information. Research being currently conducted during NMFS surveys using dredges with varying selectivity could potentially provide information that can be incorporated into the model in the future.

Other sources of uncertainty include the annual recruitment size and distribution of the clam population. The NMFS survey dataset contains information of potential use in ferreting out spatial variations in recruitment dynamics, but no such analyses have been conducted and the survey dataset is relatively sparse to support this type of endeavor in its current state. In order to account for these uncertainties, simulations have been created at a range of recruitment levels and degrees of patchiness. Finally, the abundance of the surfclam stock has historically fluctuated substantially. Future trends are difficult to foresee clearly; thus, the influence of area management at various stock abundances is a prudent addition to the simulation portfolio.

Additional assumptions are made regarding the stock, climate, and commercial fishery over the timespan that data is collected (76 years). It is likely that range contraction will continue over the simulated future; however the extent to which the contraction would continue is difficult to assess and thus the set of simulations used in this project have a static climate and range. Temperature changes over time will lead to a reduction in habitat size, but the effect of this reduction is also unknown. Even if the range of clams were to change over the 76 years during which data is collected, it is unlikely that there would be a change in the outcomes of area management discussed here. Other factors that are assumed to be static are the demand for clams (i.e. fishing pressure) and boat technologies (i.e. the ability to harvest clams at a more efficient or faster rate).

Finally, the simulations do not include a presumed increase in fertilization efficiency as surfclam density increases within closed TMSs, as is thought to be happening in the sea scallop stock. Thus, increases in stock abundance are likely to represent a lower bound on expected outcomes.

Area Management Influence on *Spisula solidissima* Stock

Performance metrics used to evaluate the influence of area management on the *Spisula solidissima* stock are stock density of clams that are recruited to the fishery (i.e. greater than or equal to 120 mm shell length), the amount of unused quota (number of cages), yield (lb bu^{-1}), and the number of clams per bushel. The outcomes of using closure location Rule 1 suggest greater improvement of the stock (i.e. growth in stock size and also the size of landed clams) than closure location Rule 2 (Table 10). Stock density shows percent increases of 4% to 7% using closure Rule 1. To put these values in perspective, the increase seen is more than double the fraction of the stock removed by the fishery in a given year and very near the exploitation rate for the area of highest exploitation offshore New Jersey. The amount of unused quota is of interest to managers in order to understand how results relate to the distribution of ITQ's used in this fishery's current management. The amount of unused quota is increased in 14% of simulations for the 3- and 5-year closure durations and 41% for the 7-year closure duration. Yield is the amount of meat that is obtained from the clams; however, it is the most difficult value to accurately simulate and thus is the weakest performance metric. A useful surrogate is the number of clams per bushel as larger clams yield more meat on average. Tracking the number of clams per bushel also is one way to investigate the status of the stock in relation to growth rates. A thriving stock will have larger clams and the fishery will take fewer clams to fill a bushel. That is, landing larger clams results in fewer individuals being removed from the population, thus enhancing stock density under a specified quota. One of the critical characteristics of the fishery is that fishing economics and fishery management are specified in terms of volume, whereas the stock itself is best defined in terms of numbers of individuals. Yield is larger in an average of 25%, 33%, and 22% of simulations (Table 2). The number of clams per bushel is significantly lower under area management in an average 31% of simulations and 100% of the 5- and 7-year closure duration simulations, regardless of the definition of a small clam.

An increase of 4% in the number of clams required to fill a bushel using present-day management equates to about three clams extra per bushel when compared to alternative management. Three fewer clams per bushel translates to around 3 fewer bushels being required to fill a cage. Annually, approximately 1,040 cages would remain in the stock, as they would not be needed to fill the cages during fishing trips. About 18 extra trips of a boat capable of carrying 56 cages could be supported. Based on percent of simulations that indicates improvement of the stock and the margins of increase, the 5-year closure duration under location Rule 1 offers the most benefit to the stock and thus is identified as the preferred option.

Area Management Influence on the Commercial Fishery

Performance metrics used to evaluate the influence of area management on the *Spisula solidissima* fishery are LPUE (bu hr^{-1}), the number of TMSs visited during fishing, and the total distance traveled during fishing. Closure location Rule 1 results in greater opportunities for the commercial fishery (Table 10). Using closure location Rule 1, LPUE is increased significantly over all definitions of a small clam in an average of 61%, 64%, and 44% of simulations (Table 4). The greatest percent increase of LPUE using Rule 1 produced enough time saved at sea to enable transit for an additional 9 nautical miles, or the addition of one TMS in any direction from the port, increasing the fishable area under the dock-to-dock time constraint imposed by the rate of spoilage of caught clams on deck. With an increase in incidental mortality, the extra time saved by an increase of 15% in LPUE allows for the boats to travel to two additional TMS in the same amount of time (approximately 36 hours from the start of fishing to landing of the clams). A 6% increase in LPUE would result in a boat that is capable of carrying 56 cages (32 bushels = 1 cage) filling all cages about 2 hours faster per trip. Being able to fill the boat on average 2 hours faster per trip would allow time for six additional fishing trips per year. A 15% increase in LPUE would equate to a reduction of five hours of fishing time per trip, a total of 15 trips annually (each trip lasting 34 hours including steam time). As fuel use is highest while fishing (both the main engine and water pump are running), any increase in LPUE exerts an important economic gain in reducing the cost of fuel relative to the value of the landed clams.

The number of TMSs visited during fishing increases significantly in an average of 6% of simulations over all closure durations and definitions of a small clam. A reduction in the number of TMSs visited suggests that the TMSs that are recently open are being targeted by captains, who choose a fishing location based on the highest catch rate. The distance traveled during fishing also increases significantly in up to 58% of simulations. An increase in distance suggests that the TMSs closed are close to the ports and that captains are traveling farther away from the ports to fish. It is beneficial for a vessel to travel the shortest distance possible to fill the quota allotted. Evaluating the distances traveled in each management procedure allows for an estimation of the duration and cost of a fishing trip. Reduced distance is preferred by commercial leaders in order to reduce operational costs, thus increasing profit margins, unless additional distance has a negligible overall effect on trip costs. This would be the case if LPUE also increases, as it does in these simulations. If a vessel steams for eight hours at a speed of 10 knots, a 4% increase in distance traveled would result in approximately an additional 4 nautical miles, which would allow for fishing one additional TMS away from port without substantial additional costs if that TMS yielded a higher LPUE. Based on percent of simulations that indicate additional economic opportunities offered to the commercial fishery, the 5-year closure duration under location Rule 1 offers the most benefit to the stock and thus is identified as the preferred option.

Influence of Control Rules

The criteria on which to base a closure location is important to the success of management in offering enhanced stock densities and additional economic opportunity to the industry. Two closure location rules were investigated that represent end-members of a range of choices for a control rule; one places importance on the number of small clams in relation to market-sized clams (Rule 1) and the other places importance on the density of small clams in an area (Rule 2). Optimizing area management would require evaluation of the influence of combined rules such as the TMS with the highest density of small clams among the 25% of TMSs with the highest proportion of small clams.

At present-day abundance, a higher percent of simulations show increased stock density under closure location Rule 1 in comparison to Rule 2 and present-day management. Average percent increases in stock density are also higher under closure Rule 1. Rule 1 places importance on the proportion of small clams. Accordingly, an increase in stock density is seen when the TMS with the greatest density of small clams in comparison to market-size clams is closed to fishing for some duration of years. Both closure location rules resulted in an average of 64% of simulations having increased LPUE when compared to present-day management (i.e. no closures). A higher average percent of increase resulted from the use of closure location Rule 2. However, closure Rule 1 resulted in an increase in LPUE as the closure duration increased, as opposed to a gradual decline seen when using Rule 2. An increase in LPUE when high importance is placed on the presence small clams suggests that protecting small clams is a key factor in offering more economic opportunity to the industry.

The percent of simulations with greater amounts of unused quota is larger using Rule 1, and the maximal percent of increase is 4% for any simulation where the amount is significantly different from present-day management. The yield was increased by less than 1% for any alternative management strategy that was significantly different from present-day management under either closure location rule. Yield, as simulated, does not include the variation in condition that comes from local variations in net production imposed by changes in temperature and food supply, so that only the most general inferences can be made from this metric. No substantial difference results from using closure location Rule 1 or 2 in the percent of simulations where the yield of clams per bushel is greater. Moreover, the average percent increase in the number of clams per bushel, a metric directly related to the size of landed clams, is essentially equivalent between both closure location rules. When the choice of closure location is based on the ratio of small clams to market-sized clams (Rule 1), the percent of simulations where fewer TMSs fished was much higher. This suggests that captains are targeting recently open TMS because they have the highest catch rates (i.e. greatest density of market-sized clams). When the closure location is based on the ratio of small clams to market-sized clams, transit distance was increased in substantially fewer simulations than under present-day management. A decrease in distance traveled when comparing Rule 1 to Rule 2 suggests that when importance is placed on the ratio of small clams relative to market-sized clams, even though the TMSs closed are near ports, once open they can provide improved local catch rates more often than if the location of the closed TMS was selected based on the abundance of small clams alone. Since some of the performance metrics (e.g. yield and number of clams per bushel) showed little difference between the two closure rules, a third option combining the two rules may offer additional benefits to the commercial fishery.

Influence of Changes in Stock Abundance

Although data exist for past population abundances, future recruitment events cannot be projected adequately. For this reason, performance metrics were investigated for a range of abundances from a level just above what would trigger quota reduction to levels above the present day abundance. Alternative management has a more positive effect on stock abundance at low abundances. Although the percent of simulations that reports increased LPUE deteriorates as abundance drops, the preferred closure duration option (five years using location

Rule 1) still results in LPUEs that show increases comparable to simulations at present-day abundance levels. An increase in the amount of unused quota at low abundances (when compared to the base case) is concurrent with an increase in the percent of simulations with larger distances traveled when fishing. The increase in the percent of simulations with more unused quota, decreased LPUE, and increased distance traveled results from TMSs being closed close to ports and that TMSs that yield the highest LPUEs are in recently opened areas. Fewer TMSs being fished under alternative area management suggests that captains target the recently open TMSs to meet quotas, particularly when abundance is low. Captains choose to fish the TMS with the highest catch rate. Targeting the recently open TMSs suggests that the alternatively-managed TMSs have the greatest stock density and this density is increased as the duration of the closure is increased when the abundance is lower than present-day.

Influence of Incidental Mortality

Little information exists about the incidental mortality of clams intersected by the dredge but that remain on the bottom. NEFSC (2013) assumes 12% incidental mortality, but this is based on very little data and primarily on the outcome for market size clams, few of which remain uncaught with modern high-performance hydraulic dredges. The fate of small clams is effectively unknown. An important portion of this project is the investigation of the effect of area management with 0% and 20% incidental mortality. An additional base case identical to the present-day simulation with increased incidental mortality was created along with an additional set of simulations with increased incidental mortality. Pair-wise comparisons of the present-day management simulation with increased mortality and simulations using area management with increased incidental mortality produced performance metrics that were then compared to the performance metrics with 0% mortality. Additional mortality enhanced the effect of area management in most situations using closure location Rule 1. The percent of simulations with enhanced performance metrics under area management was greater with increased incidental mortality. Also, the average percent increase was enhanced. In most simulations using closure location Rule 2, increased incidental mortality had little effect on the percent of simulations with improved performance metrics. The most notable difference between the percent of simulations with improved performance metrics when comparing the two levels of incidental mortality is seen in the total distance traveled. A larger percent of simulations with increased distance traveled is seen with 0% incidental mortality in comparison to simulations with 20% incidental mortality. A large effect of incidental mortality using Rule 1 and a small effect using Rule 2 suggests that a combination of the two closure location rules could offer some clarity to the real effect of increased incidental mortality. The enhancement of the effect of area management at increased levels of incidental mortality can be attributed to the protection of clams in closed areas. The effect of area management is enhanced because TMSs with high clam abundances (regardless of the closure rule) are protected, and thus fewer are removed from the stock as a result of incidental mortality. When incidental mortality is increased from 0% to 20%, mortality is increased in areas that are fished; however, in the closed areas this mortality is not occurring and these regions have the highest number of clams that would be subject to this source of mortality.

Reprisal

The importance of the presence and abundance of small clams becomes apparent upon examining the performance metrics that suggest improvement over present-day management. Of the two closure location rules, the rule that places importance on a population dominated by small clams (Rule 1) produces a greater increase in simulated stock abundance and LPUE over time in comparison to a closure location based on the density of small clams per m^2 (Rule 2). An increase in the percent of simulations where fewer TMSs are fished suggests that the closed TMSs result in higher catch rates once open than TMSs that are not closed. An increase in the distance traveled during fishing is also seen, which results from closed TMSs being close to ports. However, increases in distance are accompanied by increases in LPUE suggesting the extra distance has a negligible net effect. No obvious difference is seen between the two closure location rules for the size of landed clams (i.e. the number of clams per bushel). The amount of unused quota and yield result in average percent increases of less than 5%, suggesting that neither closure duration effects these performance metrics meaningfully.

Simulations indicate that the 5-year closure duration reaps the largest benefits to the stock and also the industry. Although average percent increases in stock density and LPUE are greater when the duration is longer, the percent of simulations showing improvement over present-day management is greatest using the 5-year closure duration. When the 5-year duration was used, the percent of simulations with greater amounts of unused quota is also lowest. Based on the improvements in performance metrics seen with closure Rule 1 and the 5-year closure duration simulations, the suggested preferred option to offer simultaneously additional opportunities for growth of the stock and improvements to the commercial fishery is to close areas specified by Rule 1 for a duration of 5 years.

APPENDIX A

TABLES

Table 1

Structure of Each Set of Cases

Abundance	Patchiness	Captain Type
High	High	Standard Confident Survey
	Medium	Standard Confident Survey
	Low	Standard Confident Survey
Present	High	Standard Confident Survey
	Medium	Standard Confident Survey
	Low	Standard Confident Survey
Low	High	Standard Confident Survey
	Medium	Standard Confident Survey
	Low	Standard Confident Survey

Note. Twenty-seven individual simulations represent one set of cases.

Table 2

Evaluation of Simulations Examining Area Management Influence on Spisula solidissima Stock Using Location Rule 1

Stock Density												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.44	0.44	0.11	0.11	0.11	0.00	0.22	0.11	0.11	0.33	0.22	0.56
Alternative management	0.44	0.33	0.56	0.44	0.67	0.44	0.56	0.56	0.44	0.22	0.33	0.33
Amount of unused quota												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.00	0.00	0.22	0.22	0.22	0.11	0.11	0.22	0.22	0.33	0.33
Alternative management	0.11	0.22	0.33	0.22	0.11	0.44	0.11	0.11	0.44	0.11	0.11	0.44
Yield												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.11	0.11	0.00	0.00	0.00	0.11	0.00	0.11	0.00	0.00	0.33
Alternative management	0.22	0.00	0.00	0.33	0.33	0.33	0.11	0.56	0.22	0.33	0.44	0.33
Number of clams per bushel												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.56	1.00	1.00	0.22	1.00	1.00	0.22	1.00	1.00	0.22	1.00	1.00
Alternative management	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note. The proportion of simulations where metrics used to evaluate the *Spisula solidissima* population were significantly greater under present-day management or alternative management using closure location Rule 1 with present-day abundance. Number of simulations per percentage = 9. Any fraction over 0.11 (one significant difference out of nine) is unlikely to occur by chance (exact binomial test: α = 0.05, Conover 1980).

Table 3

Evaluation of the Influence of Increased Incidental Mortality Using Location Rule 1

Stock Density												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.44	0.33	0.56	0.44	0.67	0.44	0.56	0.56	0.44	0.22	0.33	0.33
20% incidental mortality	0.56	0.78	0.78	0.44	0.78	0.78	0.22	0.56	0.67	0.22	0.56	0.56
Amount of unused quota												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.11	0.22	0.33	0.22	0.11	0.44	0.11	0.11	0.44	0.11	0.11	0.44
20% incidental mortality	0.11	0.11	0.11	0.44	0.11	0.11	0.22	0.33	0.11	0.56	0.22	0.22
Yield												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.22	0.00	0.00	0.33	0.33	0.33	0.11	0.56	0.22	0.33	0.44	0.33
20% incidental mortality	0.33	0.56	0.33	0.22	0.56	0.44	0.22	0.22	0.44	0.11	0.44	0.67
LPUE												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.44	0.33	0.56	0.67	0.56	0.44	0.78	0.78	0.33	0.56	0.89	0.44
20% incidental mortality	0.67	0.78	0.56	0.67	0.89	0.78	0.44	0.67	0.56	0.22	0.67	0.78
Number of TMSs fished												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.22	0.00	0.11	0.11	0.00	0.00	0.11	0.00	0.00	0.33	0.00	0.00
20% incidental mortality	0.22	0.00	0.11	0.00	0.00	0.11	0.11	0.11	0.11	0.11	0.00	0.00

Table 3 (continued).

Total distance traveled												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.33	0.56	0.78	0.11	0.44	0.67	0.33	0.44	0.44	0.22	0.44	0.44
20% incidental mortality	0.11	0.33	0.56	0.56	0.22	0.44	0.33	0.44	0.44	0.33	0.22	0.44

Note. The proportion of simulations where metrics used to evaluate the *Spisula solidissima* population and the effect of area management on the commercial industry were significantly greater under alternative management with 0% or 20% incidental mortality using closure location Rule 1 with present-day abundance. Number of simulations per percentage = 9. Any fraction over 0.11 (one significant difference out of nine) is unlikely to occur by chance (exact binomial test: α = 0.05, Conover 1980).

Table 4

Evaluation of Simulations Examining Area Management Influence on Spisula solidissima Commercial Fishery Using Location Rule 1

LPUE												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.11	0.11	0.00	0.00	0.11	0.11	0.00	0.11	0.00	0.00	0.44
Alternative management	0.44	0.33	0.56	0.67	0.56	0.44	0.78	0.78	0.33	0.56	0.89	0.44
Number of TMSs fished												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.44	0.56	0.67	0.33	0.44	0.56	0.44	0.56	0.44	0.44	0.44	0.56
Alternative management	0.22	0.00	0.11	0.11	0.00	0.00	0.11	0.00	0.00	0.33	0.00	0.00
Total distance traveled												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.11	0.00	0.00	0.11	0.00	0.00	0.00	0.11	0.00	0.11	0.00	0.00
Alternative management	0.33	0.56	0.78	0.11	0.44	0.67	0.33	0.44	0.44	0.22	0.44	0.44

Note. The proportion of simulations where metrics used to evaluate additional economic opportunity were significantly greater under present-day or alternative management using closure location Rule 1 with present-day abundance. Number of simulations per percentage = 9. Any fraction over 0.11 (one significant difference out of nine) is unlikely to occur by chance (exact binomial test: $\alpha = 0.05$, Conover 1980).

Table 5

Evaluation of Simulations Examining Area Management Influence on Spisula solidissima Stock Using Location Rule 2

Stock Density												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.33	0.11	0.11	0.22	0.00	0.22	0.00	0.11	0.11	0.33	0.00	0.11
Alternative management	0.33	0.44	0.56	0.44	0.33	0.44	0.44	0.67	0.56	0.22	0.56	0.00
Amount of unused quota												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.11	0.22	0.22	0.22	0.33	0.33	0.56	0.33	0.11	0.22	0.44	0.00
Alternative management	0.11	0.11	0.11	0.00	0.11	0.33	0.00	0.00	0.22	0.11	0.00	0.33
Yield												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alternative management	0.33	0.33	0.22	0.56	0.56	0.33	0.78	0.33	0.22	0.33	0.56	0.22
Number of clams per bushel												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.67	0.89	0.89	0.78	0.89	1.00	0.67	1.00	1.00	0.33	0.89	1.00
Alternative management	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note. The proportion of simulations where metrics used to evaluate the *Spisula solidissima* population were significantly greater under present-day or alternative management using closure location Rule 2 with present-day abundance. Number of simulations per percentage = 9. Any fraction over 0.11 (one significant difference out of nine) is unlikely to occur by chance (exact binomial test: α = 0.05, Conover 1980).

Table 6

Evaluation of the Influence of Increased Incidental Mortality Using Location Rule 2

Stock Density												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.33	0.44	0.56	0.44	0.33	0.44	0.44	0.67	0.56	0.22	0.56	0.00
20% incidental mortality	0.22	0.33	0.44	0.56	0.22	0.44	0.44	0.56	0.56	0.22	0.44	0.22
Amount of unused quota												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.11	0.11	0.11	0.00	0.11	0.33	0.00	0.00	0.22	0.11	0.00	0.33
20% incidental mortality	0.22	0.33	0.22	0.11	0.11	0.33	0.22	0.22	0.22	0.22	0.22	0.22
Yield												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.33	0.33	0.22	0.56	0.56	0.33	0.78	0.33	0.22	0.33	0.56	0.22
20% incidental mortality	0.56	0.44	0.33	0.78	0.22	0.44	0.78	0.56	0.56	0.56	0.78	0.22
LPUE												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.56	0.67	0.44	0.56	0.44	0.33	0.89	0.67	0.67	0.56	0.78	0.22
20% incidental mortality	0.44	0.44	0.33	0.67	0.22	0.44	0.67	0.67	0.56	0.33	0.56	0.44
Number of TMSs fished												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	0.67	0.22	0.00	0.11	0.00	0.00	0.22	0.00	0.00	0.22	0.00	0.11
20% incidental mortality	0.22	0.00	0.00	0.11	0.00	0.00	0.22	0.00	0.00	0.11	0.11	0.00

Table 6 (continued).

Total distance traveled												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
0% incidental mortality	1.00	1.00	0.89	1.00	0.89	0.78	0.89	0.89	0.89	0.89	0.78	1.00
20% incidental mortality	0.44	0.67	0.67	0.33	0.67	0.56	0.22	0.56	0.67	0.67	0.56	0.67

Note. The proportion of simulations where metrics used to evaluate the *Spisula solidissima* population and the effect of area management on the commercial industry were significantly greater under alternative management with 0% or 20% incidental mortality using closure location Rule 2 with present-day abundance. Number of simulations per percentage = 9. Any fraction over 0.11 (one significant difference out of nine) is unlikely to occur by chance (exact binomial test: α = 0.05, Conover 1980).

Table 7

Evaluation of Simulations Examining Area Management Influence on Spisula solidissima Commercial Fishery Using Location Rule 2

LPUE												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.11	0.11	0.00	0.00	0.11	0.00	0.00	0.11	0.11	0.00	0.22
Alternative management	0.56	0.67	0.44	0.56	0.44	0.33	0.89	0.67	0.67	0.56	0.78	0.22
Number of TMSs fished												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.11	0.44	0.00	0.11	0.22	0.11	0.22	0.44	0.00	0.33	0.44
Alternative management	0.67	0.22	0.00	0.11	0.00	0.00	0.22	0.00	0.00	0.22	0.00	0.11
Total distance traveled												
Definition of a small clam	104 mm			93 mm			80 mm			64 mm		
Closure duration	3	5	7	3	5	7	3	5	7	3	5	7
Present management	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Alternative management	1.00	1.00	0.89	1.00	0.89	0.78	0.89	0.89	0.89	0.89	0.78	1.00

Note. The proportion of simulations where metrics used to evaluate additional economic opportunity were significantly greater under present-day or alternative management using closure location Rule 2 with present-day abundance. Number of simulations per percentage = 9. Any fraction over 0.11 (one significant difference out of nine) is unlikely to occur by chance (exact binomial test: α = 0.05, Conover 1980).