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The effect of abundance changes on a management strategy evaluation for the Atlantic surfclam (*Spisula solidissima*) using a spatially explicit, vessel-based fisheries model

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ABSTRACT

Increased bottom water temperatures have caused a relocation and contraction of the range of the Atlantic surfclam, *Spisula solidissima*, in the Mid-Atlantic Bight (MAB). Consequences include declining stock abundance and landings per unit effort (LPUE) in southern portions of the range. A management strategy evaluation (MSE) assessed the potential of rotational closures to improve surfclam productivity and fishery viability under three levels of abundance. In simulations, fishing vessels harvest the stock under performance and quota constraints and captain behavioral proclivities. Management alternatives examined included the addition of area management to the current management plan using two closure location rules and three closure durations at two levels of incidental mortality. Simulations showed that area management increased stock abundance and fishery LPUE, particularly when surfclam abundance was low. Simulations suggest area management could help insulate the stock and commercial fishery from further shifts in range.

1. Introduction

Uncertainty is the bane and challenge of fishery assessment and management. Although the sources of uncertainty arise in manifold ways, environmental fluctuations and climate change affecting stock abundance and distribution often are important contributors (Lauck et al., 1998). Although extensive datasets exist from survey time series recording historical changes in population dynamics for some species, current and future recruitment events, changes in abundance, and alterations in mortality rates are difficult to measure and project due to these indefeasible uncertainties. Stock assessment methods for many species are well established; however, underlying and unavoidable ambiguity of environmental fluctuations and population characteristics prevails and precaution leading to conservative estimates is the typical mitigatory tool. For species such as the Atlantic surfclam (*Spisula solidissima* [Dillwyn, 1817]), sensitivity to climate change, particularly warming bottom water temperatures, can lead to rapid changes in abundance (Kim and Powell, 2004; Weinberg et al., 2005; Hofmann et al., 2018). High densities of surfclams can negatively affect maximum size and growth rate (Fogarty and Murawski, 1986; Cerrato and Keith, 1992; Weinberg, 1998). A consequent discrepancy in estimated current and future abundances may have long-term effects on the results of fishery management (González-Costas et al., 2016). For these reasons, investigation of the robustness of management practices to differing levels of abundance, among other varying states of nature such as spatial distribution, is important when determining best management practices (González-Costas et al., 2016).

The Atlantic surfclam is a commercially important long-lived bivalve that is a biomass dominant over much of the western North Atlantic Ocean inner continental shelf from Georges Bank in the north to the southern reaches of the Mid-Atlantic Bight (MAB) off northern North Carolina at depths of 10 m–50 m (Ropes and Merrill, 1973; Prior et al., 1979; Goldberg and Walker, 1990; Weinberg, 1998; Cargnelli et al., 1999; Jacobson and Weinberg, 2006; NEFSC, 2013). Atlantic surfclams are essentially sessile, burrowing clams that are distributed in patches where sandy bottoms are found (Fay et al., 1983). Atlantic surfclams typically reach market-size within 6–7 years depending on food availability and water temperatures (Weinberg, 1998; Cargnelli

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et al., 1999; Weinberg et al., 2002; NEFSC, 2013). Temperatures above 20 °C negatively affect growth rates and increase mortality rates, particularly for the adults larger than market size[1] (Kim and Powell, 2004; Narváez et al., 2015). Since approximately 1970, the range of *S. solidissima* has been shifting north and offshore largely driven by warming bottom water temperatures. Evidence for this shift is first seen between the 1970s and the 1990s when the southern portion of the Atlantic surfclam fishery moved to ports north of the Delmarva Peninsula as a result of the contraction of the range; clams could no longer be found in Virginia and Maryland state waters (Loesch and Ropes, 1977; Cargnelli et al., 1999; Weinberg, 2005; Munroe et al., 2013; Hofmann et al., 2018; Powell et al., 2015). Declines in growth, maximum size, and tissue weight (Weinberg, 1998, 1999) were followed by increased mortality in this region that resulted in decreasing population abundance (Weinberg, 2005; Weinberg et al., 2005). Sometime after 1999, declining abundance resulted in the near extirpation of surfclams from the inner continental shelf off Delmarva extending northward in state waters to nearly the whole of the New Jersey coast. More or less simultaneously, expansion of the population on Georges Bank occurred, abundance increased off the coast of Long Island, NY, and an offshore shift in distribution occurred off New Jersey, all in response to increased (up to +3 °C in late summer in some regions) bottom water temperatures (Powell, 2003; Kim and Powell, 2004; Weinberg, 2005; NEFSC, 2013). Simulation studies have shown that mortality from thermal stress would be sufficient to cause the observed declines in abundance (Narváez et al., 2015). Histopathological examinations along the Delmarva mortality line support this inference (Kim and Powell, 2004).

Since the 1960s, *S. solidissima* has sustained a commercial fishery that reached total revenues of $29 million in 2011 (Weinberg, 1999; Weinberg et al., 2005; NEFSC, 2013). Large portions of the commercial landings within the EEZ (Exclusive Economic Zone) have been harvested along the New Jersey and Delmarva coasts since the mid-1980s and the fishery offshore New Jersey continues to be important today (Weinberg, 1999; NEFSC, 2013). Landings from this region have been declining coincident with the latest phase of range contraction, however (NEFSC, 2013). Cessation of the clam fishery in the southernmost ports coupled with declining landings, rising fishing mortality rates, and increased fishing pressure in the northern portion of the MAB due to the contraction of fishing effort has engendered concern for the sustainability of the stock off New Jersey (Powell, 2003; Weinberg et al., 2005; NEFSC, 2013). After a 20-year closure due to the risk of harvesting clams contaminated with paralytic shellfish poison (Jacobson and Weinberg, 2006), Georges Bank was reopened in 2010 (NOAA, 2012). The opening offered some relief of fishing pressures in the MAB, but vessel constraints prevent full access to the newly opened area; consequently, landings over the majority of the stock, particularly in southernmost regions continue to decline (NEFSC, 2013; NEFSC, 2017).

In response to the concern regarding sustainability of the fishery in New Jersey, a management strategy evaluation (MSE) was performed with the central focus being the addition of area management to the present management plan (Individual Transferrable Quota (ITQ) system). Temporary closures were chosen for evaluation due to the success of such measures in improving the production of shellfish fisheries (Walters, 2000; Bloomfield et al., 2012; Córdova-Lepe et al., 2012), including rotational closures in the sea scallop (*Placopecten magellanicus*) fishery in the MAB and New England regions (Cooley et al., 2015) and limited exploitation rates in the oyster fishery in Delaware Bay (Powell et al., 2008). A MSE allows for the examination of a suite of possible management actions with comparisons of performance metrics being used to identify actions that indicate the production of desired outcomes in model simulations (Smith, 1994; Butterworth and Punt, 1999; Martell et al., 2014; Punt et al., 2013a). As used here, performance metrics (specified for the present case in the Simulations section) are values identified in collaboration with leaders and stakeholders in the fishery to ensure that MSE results are understandable by all parties involved (Francis and Shotton, 1997). The Pacific halibut (*Hippoglossus stenolepis*) (Martell et al., 2014), rock lobster (*Jasus edwardsii*) (Punt et al., 2013a,b), and U.S. southeastern king mackerel (*Scomberomorus cavalla*) (Miller et al., 2010) fisheries are examples where MSEs were used to explore management alternatives (see Spillman et al., 2009; Baudron et al., 2010; Bastardie et al., 2010 for additional examples).

The objective of this study was to examine a range of management alternatives at varying levels of stock abundance with the goal of improving the Atlantic surfclam stock and fishery in the MAB, as indicated by improvements in performance metrics. Kuykendall et al. (2017) examined the case of the Atlantic surfclam stock in the MAB under surfclam abundance and distribution patterns and fleet dispersion characteristics typical of the 2000–2013 period and found that rotational closures, properly configured, could lead simultaneously to an increase in stock abundance and fishery landings per unit effort (LPUE). However, they did not examine the influence of changes in stock abundance, which might be anticipated from the recent history of MAB warming that is anticipated to continue (Saba et al., 2016; Hare et al., 2016). Of particular concern is the observed rapidity of contraction of the southern and inshore range boundary contrasted to the slower advance of the northern and offshore range boundary, resulting in a contraction in the geographic footprint of the species, consequently portending a future abundance decline. Hofmann et al. (2018) review the geographic extent and temporal progression of this range shift. Powell et al. (2016) showed that captains in the surfclam fishery have only a limited ambit within which to address declines in abundance. The source of this limitation is the sessility of the species and the limited time at sea in which the product remains marketable. Time at sea is dependent upon storage temperatures on deck, which constrains the fishing activity particularly during the summer months. Thus, the fishery requires concentrated patches of clams upon which to fish and stock declines reduce the number of potentially fishable patches. In addition, unlike many fisheries (Flaaten, 1991; Link et al., 2011; Rijnsdorp et al., 2011), vessels in the surfclam fishery have dedicated gear, namely hydraulic dredges with dedicated onboard dredge recovery and catch processing machinery that preclude the use of any other types of fishing gear. Alternative target species for this dedicated gear and also for the market place do not exist, setting aside the ocean quahog *Arctica islandica*, which may spare surfclams in certain product lines. For these reasons, understanding the influence of a range of stock abundances on the outcome of any area management option is essential.

In this study we used a simulation model to evaluate a number of spatial management scenarios. A series of model simulations designed to compare outcomes over a range of stock abundances were completed that included a range of commercial fishing behaviors, management alternatives including present day management, stock spatial distribution patterns, and incidental dredge mortality proportions. Commercial fishing behaviors are essential to include in order to capture the response and subsequent success of management actions after implementation (Bockstael and Opaluch, 1983; Hilborn, 1992; Gillis et al., 1995; Mackinson et al., 1997; Dorn, 2001; Millischer and Gascuel, 2006; Powell et al., 2015, 2016). Performance metrics (discussed in more detail in the Simulations section) were identified in collaboration with leaders from the Atlantic surfclam fishery and used in statistical comparisons between present-day[2] and alternative area management

[1] A size limit is not enforced in the surfclam fishery, but surfclam dredges typically are fully selective for 120 + mm clams. Thus, the term market-size is referent to this size class.

[2] The term 'present-day' is used herein to refer to conditions typical of the

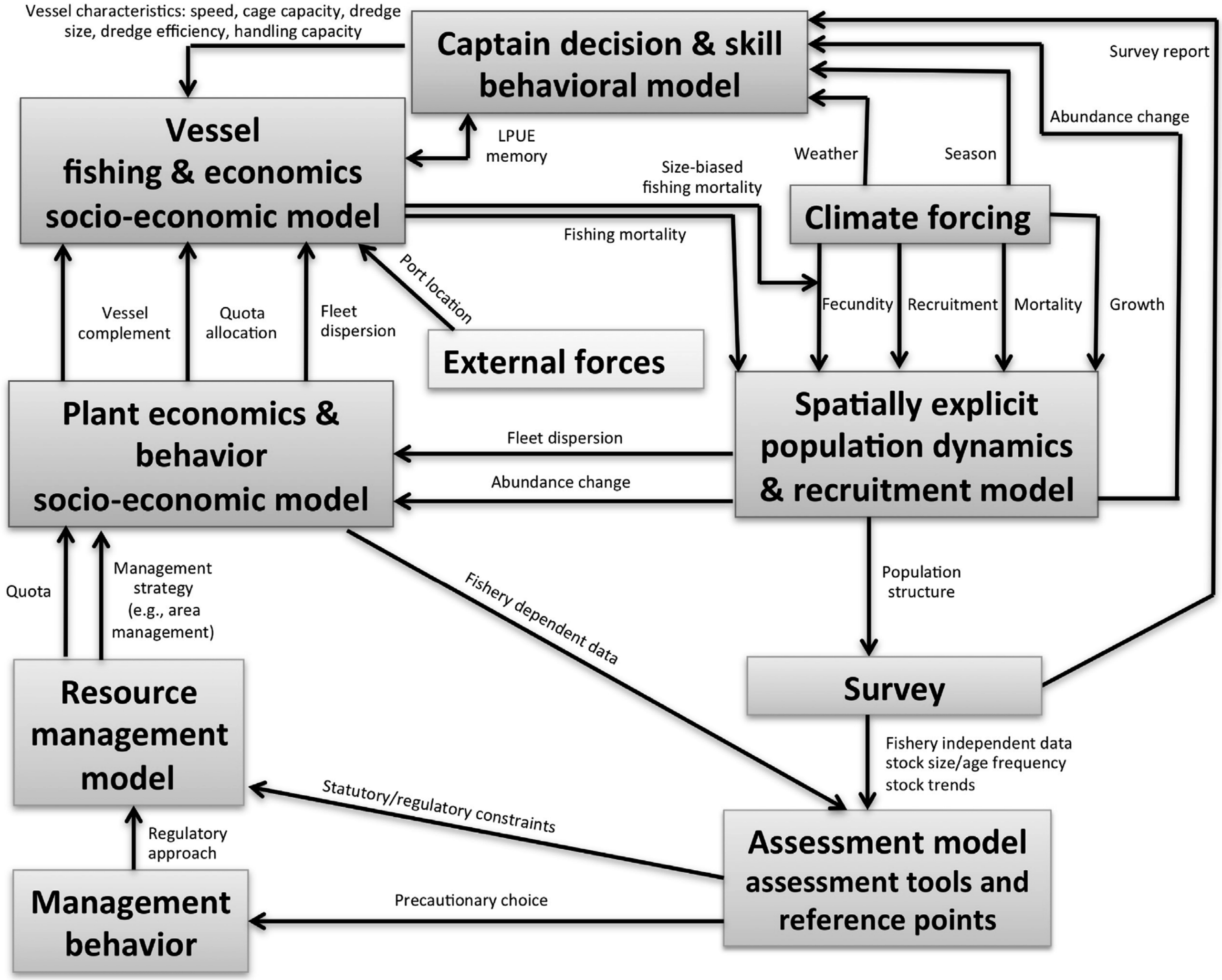

Fig. 1. Diagram adapted from Kuykendall et al. (2017) of the structure of SEFES, including all components of the model and all interactions between components used in the simulations for this study. Powell et al. (2015) provide a complete description of the capabilities of this model. Note: climate forcing controls the geographic distribution of population characteristics such as growth and mortality rates, but does not result in a change of the surfclam footprint within the domain.

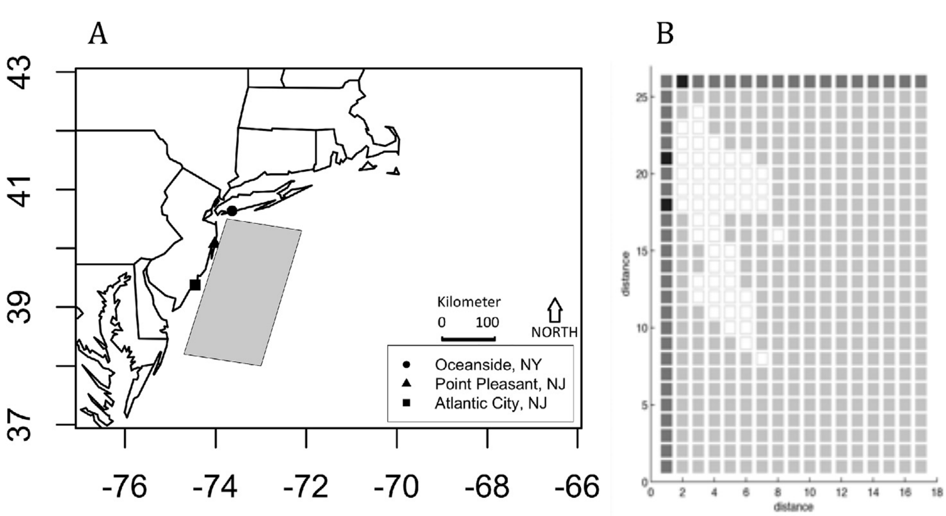

Fig. 2. (**A**) Map showing the location of home ports with a representation of the model domain in the Mid-Atlantic Bight. (**B**) Model domain with ports (black squares), fishable areas (white squares), unfishable areas (light gray squares), and land (dark gray squares). Each cell in the domain has a resolution of 10′ × 10′. The domain contains 52 ten-minute squares available to the fishery (white squares).

(*footnote continued*)
2000–2013 period offshore Delmarva and New Jersey.

options to identify management actions that offered the greatest benefit to the stock and industry, termed "preferred options" hereafter.

2. Materials and methods

2.1. MSE model description

SEFES (Spatially-explicit Fishery Economics Simulator) is an individual-based model of a temporally and spatially variable stock, *Spisula solidissima* in this case, harvested by a fleet of commercial vessels (Fig. 1). The primary model is written in Fortran 90 with post-processing in MatLab and statistical analysis using SAS (SAS Institute Inc., Cary, NC). Models that track fishing fleets spatially and/or seasonally are becoming increasingly important (Holland and Sutinen, 2000; Hutton et al., 2004; Mahévas and Pelletier, 2004; Monroy et al., 2010; van Putten et al., 2012). SEFES permits simulation of the entire fishing fleet, with each vessel operating independently according to specified criteria. Powell et al. (2015) provide a detailed model description. Pertinent details for this study are summarized in this section and in Fig. 1.

The spatial domain consists of a rectangular grid with cell areas of 10 min of latitude by 10 min of longitude (Fig. 2). The ten-minute square (TMS) corresponds to the resolution of data reported in fishery logbooks (NEFSC, 2013) and for this reason the TMS is the primary area unit used throughout this study including the selection of the size of a closed area. The grid, which is specified for the MAB, consists of 17 cells in the east-west dimension and 26 cells in the north-south dimension. Each cell, or TMS, is classified as land, fishable area, or unfishable area by a spatial mask. Three land cells specify the location of homeports located from north to south at Oceanside, NY, Atlantic City, NJ, and Point Pleasant, NJ. Of the ocean cells, 52 are fishable areas and the remaining cells are areas presently poorly inhabited or uninhabited by *S. solidissima* (Fig. 2).

Active agents in the model are nineteen commercial vessels that harvest *S. solidissima* based on imposed operational constraints and captains' decisions. Operational constraints, which can vary among vessels, include vessel speed, maximum allowed time at sea, harvest capacities, and imposed harvest quotas. Each active vessel in the fleet is specified uniquely in the model based on the operating characteristics of its archetype and is committed to 1 of 3 homeports based on the location where that vessel usually offloads its catch. The commercial vessels travel within the spatial domain and harvest *S. solidissima* based on decisions by the captains of where trip quotas can be met most efficiently (i.e., shortest time to fill the vessel with the lowest operational costs). Captains' decisions are based on memories that are built from information regarding LPUEs for TMSs that were fished. The memory of LPUE for a TMS fished during a trip is updated after each trip. See Powell et al. (2015) for a more detailed description of captain memory development.

Each simulation has a total duration of 201 years. The time step is in days with certain fishing activities occurring in hours; data for evaluation of performance metrics are collected annually. Model days are converted to calendar dates to allow for seasonal variability in weather and fishing behaviors (e.g., although the fishery operates year-round, fewer trips are taken during winter months). No fishing occurs in the first 100 years of each simulation to allow the *S. solidissima* population to reach a carrying capacity with specified abundance (i.e., levels representative of low, present-day, or high abundance - see below for further description) and local patchiness and with regional characteristics consistent with the latitudinal and cross-shelf temperature gradients. In the next 25 years, historical fishing practices are imposed during which time the captains' memories develop and the stock is harvested to a desired and specified level. Area management is imposed in simulation year 126 and the final 76 years are used to evaluate the area management option relative to the scenario of present-day management. Surfclam life span is about 30 yr, with few animals surviving past about 25 yr (Weinberg, 1999); thus 76 years is about three times the typical life span of the species.

Three initial stock distributions were specified to cover a range in stock patchiness. Patchiness was established by assigning new recruits to each TMS using a negative binomial random distribution that produces distinctive variance in the abundance of clams in each TMS relative to the mean abundance for all TMSs. The range of patchiness used in this study is typical of bivalve populations and consistent with federal survey data (Kuykendall et al., 2017). An Allee effect was not included: population densities are assumed not to limit fertilization efficiency. Because the dynamics of any future range shift are uncertain and because the duration investigated for individual area closures was short in comparison to the species' life span, simulations assumed a stable geographic footprint.

Larval recruitment is an annual event. The recruitment rate is derived from a deterministic broodstock-recruitment relationship (Powell et al., 2015). Post-settlement abundance, the focus of this study, is determined by modifying the larval recruitment rate relative to the broodstock present without changing the form of the broodstock-recruitment curve. The levels are labeled low (abundance is maintained somewhat above the trigger for quota reduction), present-day (representative of present-day abundances), and high (roughly twice the abundance of present-day). The abundance levels are established by varying recruitment rate relative to mortality rate and are allowed to stabilize during the first 100 years. Although bivalve density effects on growth are well described (e.g., Fréchette and Lefaivre, 1990; Powell et al., 1995; Beukema and Dekker, 2015), no growth penalty was included in the high-abundance case because abundances of this scale are routinely observed in surfclam patches throughout the stock range without report of limitations in growth or maximum size. Thus, trophic interactions were not included in the simulations.

Surfclams are distributed in length-based size classes. Average wet weights (W in g) are calculated with an allometric relationship of the form (Marzec et al., 2010):where L is the length in mm. Parameter values come from Marzec et al. (2010). Growth and mortality rates vary latitudinally and across-shelf for each TMS. The growth rate of *S. solidissima* is calculated from a von Bertalanffy growth curve with a rate (k) that increases in the northern and eastward direction using the equation:

$$L_A = L_\infty(1 - e^{-kA})$$

where L is length in mm and A is age in years. Parameters are based on Munroe et al. (2016) and NEFSC (2013). Natural mortality is imposed using a constant mortality rate across all size classes consistent with the presently accepted stock assessment model (NEFSC, 2013) and the analysis of Weinberg (1999) and is specified to increase from northeast to southwest across the domain to reduce surfclam abundance at the southern and inshore extremes of the range as observed.

A survey of the simulated clam population is conducted annually on November 1 and includes the most recent recruitment event. The survey uses the true clam density for each TMS and samples every TMS in the domain. Results from the survey can be used to set the annual quota based on a quota cap established by the fishery management plan (FMP) (MAFMC, 1986), the biological reference points established in NEFSC (2013), and typical ABC (allowable biological catch) control rules. In reality, the surfclam ABC has always been above the FMP quota cap (NEFSC, 2013). The stock has never been overfished and overfishing has never occurred. Consequently, in these simulations, abundance was varied such that the total allowable catch remained above the FMP quota cap. Thus the yearly quota remained stable at 3.5 million bushels (i.e. the FMP quota cap): simulations address management options for a fishery in which overfishing does not occur and in which the stock is not overfished, but in which the fishery may itself be constrained by the number and locations of patches of sufficient size to sustain economic exploitation of the resource. This general scenario is consistent with the conditions present throughout the 2000 to 2017 period as documented in the most recent federal assessments (NEFSC, 2013; NEFSC, 2017).

The annual quota biomass is converted to bushels of clams. The present-day Fishery Management Plan (FMP) for Atlantic surfclams uses an Individual Transferrable Quota (ITQ) system that allocates a number of cage landings to each of the shareholders (McCay et al., 1995; MAFMC, 2013; NEFSC, 2013). In practice, these shares are amassed through direct ownership or lease by processing plants and quota flows down to the vessels each of which fishes exclusively for specific processing plants. That is, the fishery is vertically integrated with processing plants holding quota that they distribute to vessels that only land catch at designated ports. The model we present mimics this standard industry practice. Each processing plant distributes its fraction of the total quota to its vessels weekly. The weekly quota is limited to twice the vessel hold size, thus limiting the number of trips per vessel to two per week. During each simulation, vessels harvest clams based on the captain's proclivity and memory of fishing areas and imposed harvest quota. The vessels fish to capacity if possible given the constraint that time at sea is restricted during the warmer months to limit deterioration of the catch as surfclam vessels have no or limited refrigeration capacity. Harvest rates are calculated from tow speed, dredge width, dredge efficiency, and the size selectivity of the dredge based on information from the federal survey program (e.g., NEFSC, 2013) and vessel-specific data from vessel owners.

2.2. Simulations

The primary management objective is to insulate both the *S. solidissima* stock and commercial industry from further decline and identify those scenarios that promote sustainability. 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 five performance metrics vetted in interviews with representatives from processing plants, industry trade organizations, and vessel captains. Two of these monitor the population: clam fishable-stock density (i.e., the number of clams ≥120 mm shell length per square meter (NEFSC, 2013)) and the number of clams per landed bushel. The remaining three metrics monitor the effect of area management on the commercial industry: LPUE (the number of bushels fished per hour), the number of TMSs fished, and the total distance traveled per fishing trip (in kilometers). The management options include a range of closure locations and durations discussed later in this section.

Alternative hypotheses about population dynamics often termed "states of nature", such as dispersion and abundance of a stock, can cause marked differences in the success of management alternatives (Punt and Hilborn, 1997; McAllister and Kirkwood, 1998; Hilborn, 2003). The fact that recruitment can be highly variable in space (e.g., Munroe and Noda, 2009; Vassiliev et al., 2010; Nicolle et al., 2013) is well known and recent simulations of surfclam larval transport (Zhang et al., 2015, 2016) confirm inferences from stock surveys (e.g., NEFSC, 2017) that settlement is highly patchy and that the degree of patchiness is highly variable. Therefore, in this study, differences in surfclam spatial distribution anticipated to be a consistent feature of the species' population dynamics are simulated as differing degrees of patchiness 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). Three levels of stock abundance are examined (low, present-day, and high), which are achieved by scaling recruitment relative to the spawning stock biomass without changing the form of the broodstock-recruitment curve. A potential relationship between recruitment variability and population abundance (e.g., Myers, 2001) is integrated by including simulations of varying scales of patchiness at each level of abundance; however the possible biased recruitment within dense adult patches, seen in some bivalves (e.g., Williams, 1980; Peterson and Black, 1993), is not included as no evidence exists at present for this phenomenon in surfclams.

The effect of incidental mortality of clams that remain on the sea floor after dredging on different management strategies is investigated by setting incidental mortality to 0% and 20% of the clams intercepted but not retained by the dredge. Currently, incidental mortality is assumed to occur at an intermediate value of 12% (NEFSC, 2013) based on Meyer et al. (1981). For each of the degrees of patchiness, levels of abundance, and levels of incidental mortality, simulations were performed using present-day management (termed "base cases" hereafter) for comparison to simulations of area management options.

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 years to harvest (i.e., the elapsed time for a small clam of specified size to reach a defined market size) have all been identified as pertinent commercial physiognomies when considering management strategies. Powell et al. (2015, 2016) examined the effect of a range of behaviors within the standard repertoire reported from personal interviews with captains on the economics of surfclam fishing. For this study, we chose three representative behaviors that might be expected to be enhanced by the imposition of area management rules. "Standard" captains do not search for new fishing grounds and do not use survey data. These captains employ their memory of previous fishing trips to identify fishing locations. "Survey" captains update their knowledge every three years with data from NMFS stock surveys. The use of NMFS survey data by captains is a common practice and has been found to improve their performance in simulation studies (Powell et al., 2015). "Confident" captains spend 20% of fishing time searching for new fishing grounds. In simulation analysis, searching behavior at this frequency produces similar positive changes in performance as using survey data (Powell et al., 2015). Captain behaviors are mutually exclusive to each captain type (i.e., captains who search do not use survey data). These three captain types are included in each simulation set.

Each individual simulation has a defined degree of stock patchiness, level of abundance at carrying capacity, level of incidental mortality, and captain type (Table 1). Twenty-seven total simulations, one simulation for each combination of stock patchiness (n = 3), abundance (n = 3), and captain type (n = 3), constitute one set of cases, hereafter termed a series. Series are then repeated for each level of incidental mortality (Table 1).

To determine whether area management will be beneficial to the Atlantic surfclam stock and commercial fishery, performance metrics are compared between series under present-day and alternative management options (Fig. 3). Because the future distribution of captain behavioral types is unknown (i.e., how many captains will be standard, use survey data, or exhibit searching behaviors) and future changes in the spatial patchiness of clams similarly impossible to predict, analyses focused on the frequency of similar outcomes across the 3 × 3 array of captain types and population patchiness levels, the expectation being that the best choice of a management alternative was one most likely to provide positive results regardless of the mix of captain types and degrees of species patchiness. In all cases, for each performance metric, comparisons tallied in favor of any management alternative were those in which the difference between the alternative and present-day was significant at $\alpha \le 0.05$.

Management alternatives investigated were restricted to closures of only one TMS per year, with the choice based on 1 of 2 rules; a given rule remains in effect throughout the 76 simulated fishing years. If Rule 1 is executed, the TMS with the highest ratio of small clams to market-size clams 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 is closed each year. Rule 2 considers the population of small clams as a whole over an area. As

Table 1
Structure of each simulation series. Note. Twenty-seven individual simulations represent one set of cases termed a series (three levels of abundance, patchiness, and captain type). A total of 81 individual simulations were performed (one series for each of three closure durations). The 81 individual simulations were then performed for the four definitions of a small clam and each of two closure location rules for a grand total of 648 simulations. The 648 simulations were then repeated with 20% incidental mortality.

	Model configurations				Series complement		
Performance metrics	Levels of incidental mortality	Management options	Closure duration	Definitions of a small clam (mm SL)	Level of abundance	Patchiness	Captain type
Stock density (clams $\geq$120 mm/m^2)	0%	Present-day – no closures	3	104	High	High	Standard
Number of clams per bushel	20%	Rule 1 – close the TMS with the highest ratio of small clams/market-sized clams	5	93			Confident
LPUE (bu h^{-1})		Rule 2 –close the TMS with the highest number of small clams/m^2	7	80			Survey
Number of TMSs fished				64	Present	Medium	Standard
Distance traveled during fishing (km)							Confident
							Survey
					Low	Low	Standard
							Confident
							Survey

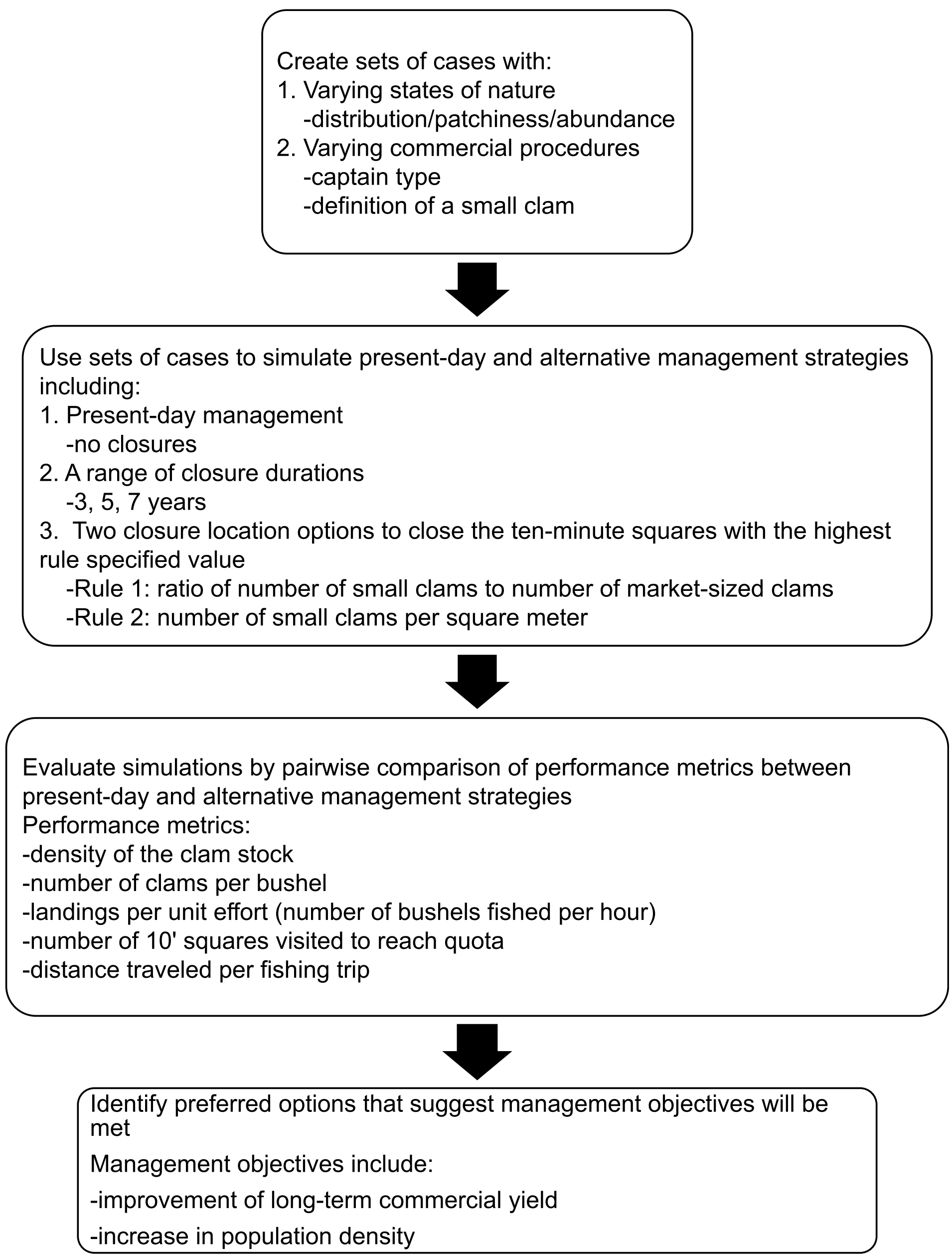

Fig. 3. Diagram of the procedure used to compare performance of present-day management (no closures) with alternate management (3 closure durations and 2 closure location rules).

the population varies yearly across the domain with larval recruitment stochastically distributed based on the level of patchiness, fishing, and the geographic variation in growth and mortality, the chosen TMS may in any given year be any one of the many potentially available. Closure durations of 3-, 5-, and 7-years are compared to no closures. This results in three, five, or seven TMSs being closed during each of the simulated years once the initial span of time specified has elapsed. The closure durations result in 6%, 10%, and 14%, respectively, of the fishable area being closed during any year after the maximum number of TMSs is closed [e.g., for the 5-year closure duration, 5 TMSs (10% of the fished area) would be closed at a given time after the first 5 years].

Success of both area management rules varies depending on the definition of a small clam (i.e., a clam that is smaller than market-size) used to identify the TMS to be closed. The definition of a small clam 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. The number of small clams is determined based on the smallest shell length that would reach market size (120 mm) in a defined period of time. All clams this size or larger in a TMS, but < 120 mm, are counted to invoke Rules 1 or 2. For convenience, an average of the minimum sizes for all TMSs is used to identify groups of clams with the same maximal elapsed time to market size 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, to reach 120 mm.

3. Results

3.1. Closure location based on Rule 1: the ratio of small clams to market-sized clams

3.1.1. Stock density

A set of simulations was performed for three levels of stock patchiness and three typical aspects of the behavioral ambit of captains. In some cases, the present-day management option outperformed the area management option. In other cases, the opposite was true. Here, we focus on the proportion of cases falling into one of these two categories because management does not impact the distribution of the stock or the proclivities of the captains. When abundance is lower than present-day, the largest proportion of simulations that show improvement to the stock with an area management option occurs with the longest closure duration of 7 years (Fig. 4, Table 2): a five year closure also performs well in comparison to present-day management regardless of the size of clam used to identify the closure location. The positive impact of a closure degrades when the duration is limited to 3 years. According to the closure rule used in these simulations, the TMS with the largest number of small clams relative to market-sized clams is closed. Thus, when the TMS is reopened, more market-sized surfclams will be present with increasingly longer closure times. At present-day abundance the largest proportion of simulations that show improvement under alternative management shifts somewhat to those with the 5-year closure duration, but the closure options continue to outperform present-day management under most closure durations and definitions of a small clam (Table 2) as shown by the higher fraction of cases where clam density was significantly higher under area management in comparison to the fraction of cases where clam density was significantly higher under present-day management in most small clam size and closure duration combinations (Fig. 4). Area management has almost no effect when abundance is higher than present-day (Fig. 4, Table 2). Unlike the cases at the two lower abundances, present-day management without area closures at high abundance often performed best. When incidental mortality is increased from 0% to 20%, the effect of area management is enhanced at all abundance levels, with the greatest effect at low abundance (Tables 3 and 5). Generally, stock density shows the most improvement when the definition of a small clam is 80 mm or 93 mm regardless of the level of incidental mortality or level of stock abundance (Tables 4 and 5).

3.1.2. Number of clams per bushel

The number of clams per bushel is determined by the average size of the animals caught. Generally, larger clams being caught reduces the impact on the stock because the quota is set in terms of biomass and converted to volume for implementation, not by number. Area closures routinely result in larger clams being landed; as a consequence, present-day management results in the landing of more clams per bushel and this is seen in the high number of simulations where present-day management “outperformed” area management using this metric (Table 2). In all simulations using the 5- and 7-year closure durations at all levels of abundance, fewer clams were required to fill a bushel (i.e. larger clams were landed) than in simulations using present-day management (Table 2). For some alternative management strategies, larger clams (fewer clams per bushel) were always landed in comparison to present-day management (Table 2). The trend was consistent across all cases that used 5- and 7-year closures. When using the 3-year closure duration, progressively larger clams were landed as the size definition of a small clam decreased from 104 to 64 mm (Table 4, Fig. 4). Fewer clams are protected when the definition of a small clam is large (i.e. 104–120 mm), with an increasingly larger number of clams being protected as the definition of a small clam decreases. The 3-year closure option limits the influence on the stock regardless of the size class basis for closure (Fig. 4). The effect of area management at high abundance is slightly muted; however, the proportion of simulations that showed larger numbers of clams per bushel (i.e. landing of smaller clams) under present-day management was still consistently greater than any alternative management (Fig. 4).

When incidental mortality is increased from 0% to 20%, the effect of area management is most significant at low and present-day abundance levels (Tables 3 and 5). With the exception of the 3-year closure duration, alternative management still resulted in the landing of larger clams. The 3-year closure duration at all abundance levels resulted in consistently more clams per bushel than present-day management with higher incidental mortality. That is, the positive influence of area management in increasing the size of clams landed was lessened. Without incidental mortality, the size of clam used to define a closure had limited effect (Table 4), whereas sizes ≥80 mm were clearly superior when incidental mortality was raised to 20% (Table 5). Population abundance, however, did not materially influence this trend.

3.1.3. Landings per unit effort

As abundance increased, the proportion of simulations that showed significant increases in LPUE using area management also increased (Fig. 5). At low abundance, the effect of area management is not as substantial; however, at both low and present-day abundance, the 5-year closure duration had the largest proportion of simulations (0.56 and 0.64, respectively) that showed a significant increase in LPUE averaged over all definitions of a small clam (Table 2). Closure duration was less important at high abundance, but area management routinely increased LPUE (Table 2). When incidental mortality is increased from 0% to 20%, the effect of area management is greatly enhanced at the two lower abundance levels (Tables 3 and 5). With rare exception, LPUE was enhanced more often when the definition of a small clam was 64 or 80 mm (Table 4). When incidental mortality is increased at high abundance the 64 mm definition of a small clam performs better, but larger clams, 80–93 mm generally performed best at the lower abundance levels (Table 5).

3.1.4. Number of ten-minute squares fished

Captains tend to return many times to individual fishing sites where LPUE is high until these patches are depleted. As a consequence, the

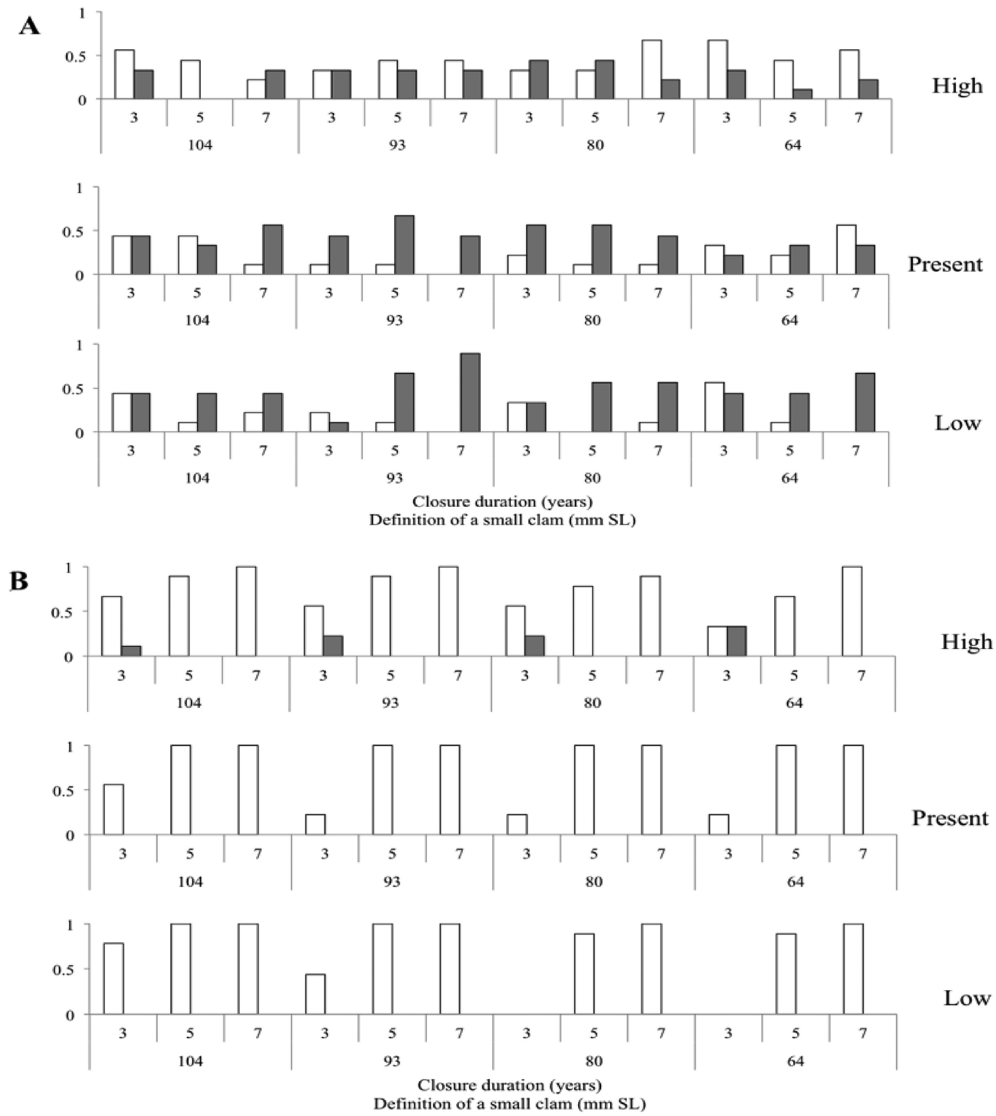

Fig. 4. The proportion of simulations where (A) stock density and (B) the number of clams per bushel were significantly higher using present-day or alternative management at high, present-day, and low abundance levels using closure location Rule 1 with 0% incidental mortality. Open bars represent the proportion of simulations where metrics were significantly greater using present-day management. Shaded bars represent the proportion of simulations where metrics were significantly greater using alternative management.

fishery tends to focus effort on a few TMSs (NEFSC, 2013). The model recapitulates this observed trend based on a few basic decisions routinely made by captains: identify the TMSs with the highest remembered LPUE; choose the closest TMS of this subset to minimize steaming time (Powell et al., 2015). More TMSs were always visited when fishing using present-day management in comparison to area management (Fig. 5, Table 2). A reduction in the number of TMSs fished using area management occurs because captains target the newly opened TMS that for a time offers increased LPUE. When incidental mortality is increased from 0% to 20%, the overall trend of present-day management resulting in more TMSs being visited when fishing remained (Tables 3 and 5). The size of clam chosen to define a closure did not materially affect the outcome with or without incidental mortality (Tables 4 and 5).

3.1.5. *Distance traveled per fishing trip*

The distance traveled per fishing trip was always greater using area management for all levels of abundance (Fig. 5). The increase in distance when using area management occurs for two reasons. Some closed TMSs are close to ports necessitating vessels traveling farther to reach open TMSs with high LPUE. Some newly opened TMSs are farther from port, but the increased LPUE offsets the increased travel time. For all levels of abundance, as the closure duration increases, the proportion of simulations with increased distance traveled increases (Fig. 5, Table 2). Longer closure durations result in more TMSs being closed at a given time, thus vessels have to travel farther to get past the increasing number of closed TMSs. The differential between the proportion of simulations that show increased distances using present-day and alternative management decreases as abundance increases (Fig. 5). The decreasing differential is expected because recently-opened TMSs near ports have higher clam densities and greater LPUEs, thereby lessoning the need to travel farther from port when abundance is high. Nonetheless, travel time increases on the average relative to present-day management.

When incidental mortality is increased from 0% to 20%, simulations continually result in farther distances traveled when fishing under present-day management (Tables 3 and 5). The differential between present-day and area management is lessoned, and dramatically so at high abundance (Tables 3 and 5). The higher LPUE diminishes the need to steam further from port. At low abundance the distance traveled is always greater than at other abundance levels regardless of the

Table 2
Tabulated are the average proportions of simulations across all definitions of a small clam (64–104 mm) that showed a significantly increased performance metric using area management in comparison to present-day management with 0% incidental mortality. The largest proportions are shown in bold for each abundance level. Proportions for the number of clams per bushel are zero because larger clams were almost always landed using alternative management. That is, in most simulation sets, all simulations showed that fewer (and therefore larger) clams would be landed using the area management option.

Performance metric	Closure duration	Abundance					
		High	Present	Low	High	Present	Low
		Closure rule					
		1			2		
Stock density	3	**0.36**	0.42	0.33	0.25	0.36	0.33
	5	0.22	**0.47**	0.53	0.25	**0.50**	0.25
	7	0.28	0.44	**0.64**	**0.33**	0.39	**0.39**
Number of clams per bushel	3	**0.22**	0.0	0.0	**0.11**	0.0	**0.03**
	5	0.0	0.0	0.0	0.0	0.0	0.0
	7	0.0	0.0	0.0	0.0	0.0	0.0
LPUE	3	**0.80**	0.61	0.33	**0.84**	**0.64**	**0.53**
	5	0.78	**0.64**	**0.56**	**0.84**	**0.64**	0.39
	7	0.78	0.44	0.17	0.72	0.42	0.39
Number of TMSs fished	3	0.0	**0.19**	0.0	**0.03**	**0.31**	**0.03**
	5	0.0	0.0	0.0	0.0	0.06	0.0
	7	0.0	0.03	0.0	**0.03**	0.03	0.0
Distance traveled during fishing	3	0.30	0.24	0.47	0.41	**0.95**	**0.89**
	5	0.53	0.47	0.70	0.47	0.89	0.84
	7	**0.64**	**0.58**	**0.73**	**0.62**	0.89	0.84

Table 3
Tabulated are the average proportions of simulations across all definitions of a small clam (64–104 mm) that showed a significantly increased performance metric using area management in comparison to present-day management with 20% incidental mortality. The largest proportions are shown in bold for each abundance level. Proportions for the number of clams per bushel are zero because larger clams were almost always landed using alternative management. That is, in most simulation sets, all simulations showed that fewer (and therefore larger) clams would be landed using the area management option.

Performance metric	Closure duration	Abundance					
		High	Present	Low	High	Present	Low
		Closure rule					
		1			2		
Stock density	3	0.33	0.36	0.59	0.36	0.36	0.44
	5	0.41	0.67	0.78	**0.47**	0.39	0.33
	7	**0.47**	**0.70**	**0.89**	**0.47**	**0.42**	**0.62**
Number of clams per bushel	3	**0.36**	**0.34**	**0.33**	**0.03**	0.0	**0.03**
	5	0.08	0.0	0.0	0.0	0.0	0.0
	7	0.0	0.0	0.0	0.0	0.0	0.0
LPUE	3	0.73	0.50	0.59	0.97	**0.53**	**0.70**
	5	0.78	**0.75**	0.72	**1.0**	0.47	0.44
	7	**0.86**	0.67	**0.89**	0.86	0.44	0.56
Number of TMSs fished	3	**0.03**	**0.11**	**0.03**	**0.03**	**0.17**	**0.03**
	5	0.0	0.03	0.0	**0.03**	0.03	**0.03**
	7	0.0	0.08	0.0	0.0	0.0	0.0
Distance traveled during fishing	3	0.08	0.33	0.53	0.19	0.42	**0.97**
	5	0.17	0.30	0.45	0.17	0.62	**0.97**
	7	**0.19**	**0.47**	**0.64**	**0.33**	**0.64**	0.81

definition of a small clam (Table 4). The smallest definition of a small clam (64 mm) results in the least increase in distance traveled at present day abundance, but overall, choice of a clam size to define closure has little differential influence on the outcome (Table 4). When incidental mortality is increased, the 80 mm definition of a small clam results in the least frequency of increased distance traveled under area management, but only at high abundances (Table 5); the 64 mm definition of a

Table 4
Tabulated are the average proportions of simulations across all closure durations (3, 5, and 7 years) that showed a significantly increased performance metric using area management in comparison to present-day management with 0% incidental mortality. The largest proportions are shown in bold for each abundance level. Proportions for the number of clams per bushel are zero because larger clams were almost always landed using alternative management. That is, in most simulation sets, all simulations showed that fewer (and therefore larger) clams would be landed using the area management option.

Performance metric	Definition of a small clam	Abundance					
		High	Present	Low	High	Present	Low
		Closure rule					
		1			2		
Stock density	104	0.22	0.44	0.44	0.22	0.44	0.26
	93	0.33	**0.52**	**0.56**	0.26	0.40	**0.37**
	80	**0.37**	**0.52**	0.48	**0.40**	**0.56**	0.33
	64	0.22	0.29	0.52	0.22	0.26	0.33
Number of clams per bushel	104	0.04	0.0	0.0	0.0	0.0	0.0
	93	0.07	0.0	0.0	0.04	0.0	0.0
	80	0.07	0.0	0.0	0.04	0.0	0.0
	64	**0.11**	0.0	0.0	**0.07**	0.0	**0.04**
LPUE	104	0.82	0.44	0.26	0.67	0.56	0.37
	93	0.74	0.56	0.41	0.78	0.44	**0.56**
	80	**0.89**	**0.63**	0.29	0.85	**0.74**	0.40
	64	0.71	**0.63**	**0.44**	**0.89**	0.52	0.40
Number of TMSs fished	104	0.0	**0.11**	0.0	**0.04**	**0.30**	0.0
	93	0.0	0.04	0.0	0.0	0.04	**0.04**
	80	**0.04**	0.04	0.0	0.0	0.07	0.0
	64	0.0	**0.11**	0.0	**0.04**	0.11	0.0
Distance traveled during fishing	104	**0.52**	**0.56**	**0.63**	**0.52**	**0.96**	0.74
	93	0.44	0.41	**0.63**	**0.52**	0.89	0.82
	80	0.48	0.40	**0.63**	**0.52**	0.89	0.89
	64	**0.52**	0.37	**0.63**	0.44	0.89	**0.96**

Table 5
Tabulated are the average proportions of simulations across all closure durations (3, 5, and 7 years) that showed a significantly increased performance metric using area management in comparison to present-day management with 20% incidental mortality. The largest proportions are shown in bold for each abundance level. Proportions for the number of clams per bushel are zero because larger clams were almost always landed using alternative management. That is, in most simulation sets, all simulations showed that fewer (and therefore larger) clams would be landed using the area management option.

Performance metric	Definition of a small clam	Abundance					
		High	Present	Low	High	Present	Low
		Closure rule					
		1			2		
Stock density	104	0.33	**0.71**	0.74	0.33	0.33	**0.48**
	93	**0.48**	0.67	**0.78**	**0.48**	0.41	0.44
	80	0.33	0.48	**0.78**	**0.48**	**0.52**	**0.48**
	64	**0.48**	0.45	0.71	0.44	0.29	0.44
Number of clams per bushel	104	0.11	0.04	0.0	0.07	0.0	0.0
	93	0.11	0.04	0.04	0.07	0.0	0.0
	80	0.11	**0.19**	0.11	0.07	0.0	**0.04**
	64	**0.26**	**0.19**	**0.30**	**0.15**	0.0	0.0
LPUE	104	0.71	0.67	0.56	0.85	0.40	0.48
	93	0.78	**0.78**	**0.82**	0.96	0.44	0.59
	80	0.74	0.56	**0.82**	**1.0**	**0.63**	0.56
	64	**0.93**	0.56	0.74	0.96	0.44	**0.63**
Number of TMSs fished	104	0.0	**0.11**	**0.04**	0.0	**0.07**	0.0
	93	0.0	0.04	0.0	0.0	0.04	0.0
	80	0.0	**0.11**	0.0	**0.04**	**0.07**	**0.07**
	64	**0.04**	0.04	0.0	**0.04**	**0.07**	0.0
Distance traveled during fishing	104	**0.22**	0.33	**0.63**	**0.37**	0.59	0.85
	93	0.11	**0.41**	0.48	0.22	0.52	0.93
	80	0.07	0.40	0.60	0.11	0.48	0.93
	64	0.18	0.33	0.44	0.22	**0.63**	**0.96**

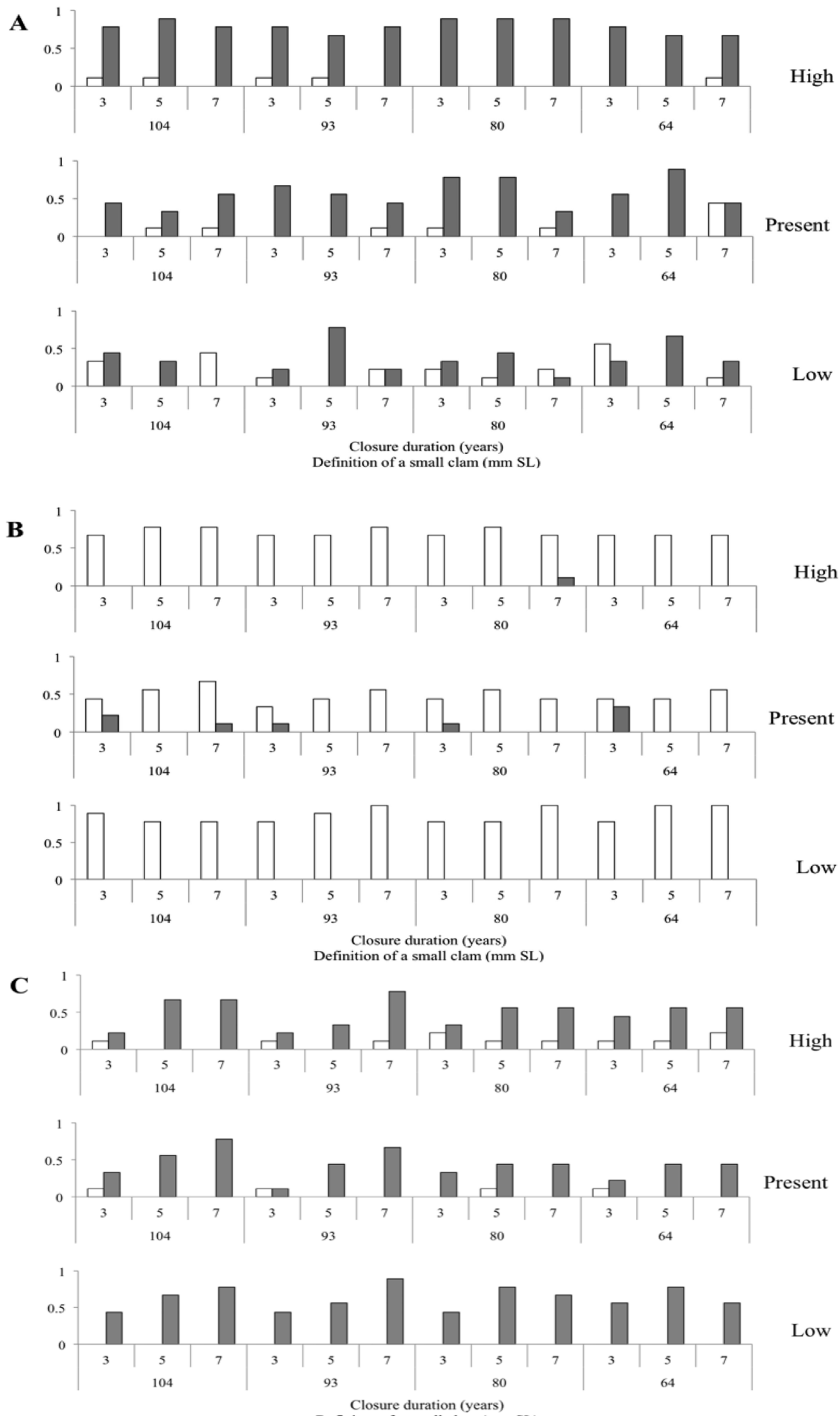

Fig. 5. The proportion of simulations where (A) landings per unit effort (LPUE), (B) the number of ten-minute squares (TMS) fished, and (C) the distance traveled when fishing were significantly higher using present-day or alternative management at high, present-day, and low abundance levels using closure location Rule 1 with 0% incidental mortality. Open bars represent the proportion of simulations where metrics were significantly greater using present-day management. Shaded bars represent the proportion of simulations where metrics were significantly greater using alternative management.

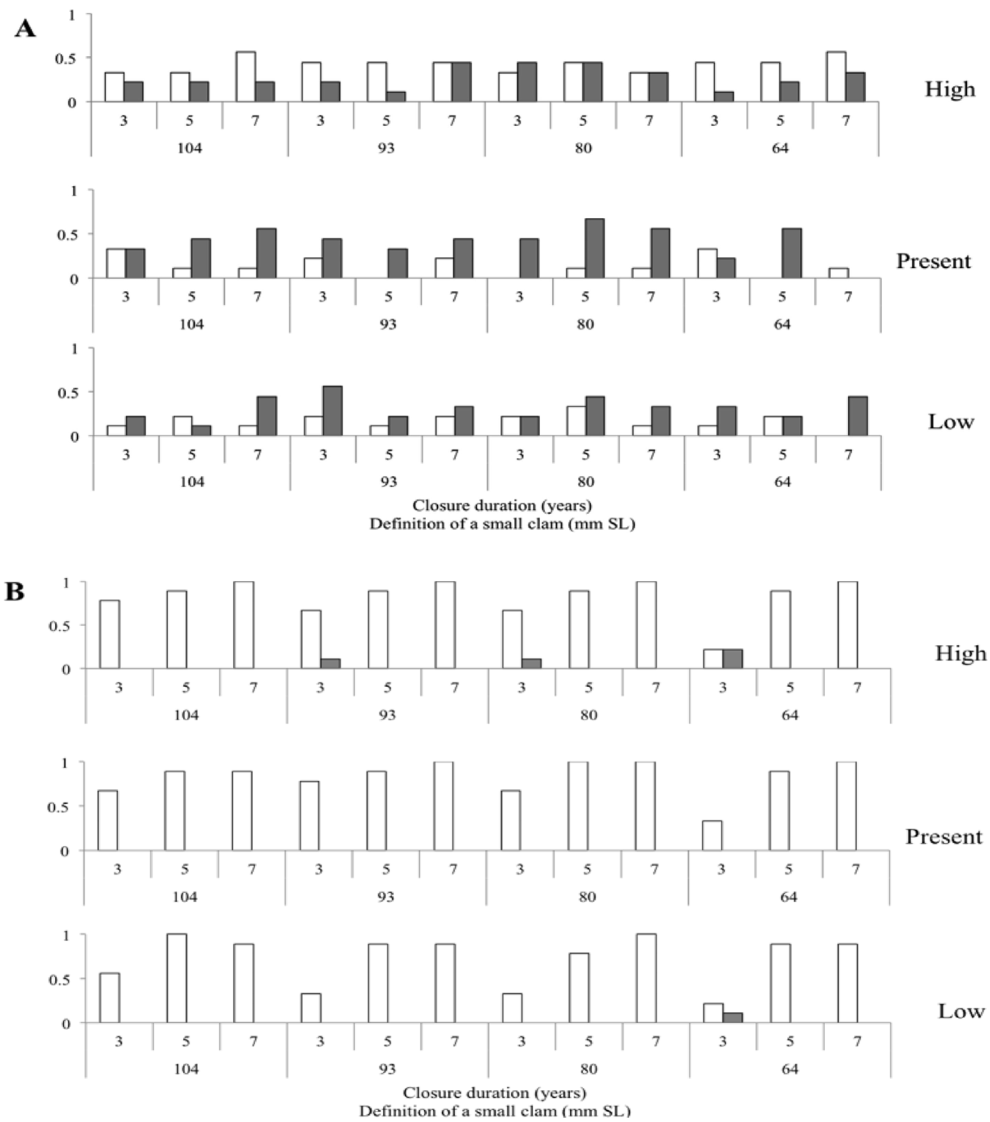

Fig. 6. The proportion of simulations where (A) stock density and (B) the number of clams per bushel were significantly higher using present-day or alternative management at high, present-day, and low abundance levels using closure location Rule 2 with 0% incidental mortality. Open bars represent the proportion of simulations where metrics were significantly greater using present-day management. Shaded bars represent the proportion of simulations where metrics were significantly greater using alternative management.

small clam resulted in the least increase in distance traveled overall (Table 5).

3.2. Closure location based on Rule 2: the number of small clams per m^2

3.2.1. Stock density

Closure rule 2 emphasizes the number of small clams present rather than their proportional contribution to the stock in the TMS. In general, the modeled trends are less predictable than those observed using Closure Rule 1, which emphasizes the proportion of clams in a TMS that are small. At low abundance, the differential in the proportion of simulations that show improvement under area management relative to present-day management tends to be larger with the 7-year closure duration under Rule 2 (Fig. 6). The 7-year closure duration results in the largest amount of area to be closed at a single time (seven TMSs at a maximum) and also allows the longest time for growth. At present-day abundance, the 5-year closure duration gives the largest proportion of simulations that show improvement under area management (Fig. 6).

The 5-year closure duration also results in the largest proportion of simulations to show improvement to the stock averaged for all definitions of a small clam (Table 2). Area management has a lesser effect at high abundances (Fig. 6). When incidental mortality is increased from 0% to 20%, the effect of area management is enhanced in most cases at low and high abundance levels, but the differential is limited at present-day abundance (Tables 3 and 5). A 7-year closure typically performed best. The 80-mm definition of a small clam generally resulted in the greatest improvements to stock density regardless of the level of incidental mortality (Tables 4 and 5).

3.2.2. Number of clams per bushel

At all abundance levels, progressively larger clams were landed as the definition of a small clam increased; in nearly all cases, present-day management resulted in smaller (more) clams being landed (Fig. 6, Tables 2 and 4). For the 3-year closure, the discrepancy between the proportion of simulations with smaller clams being landed using present-day and alternative management decreases with decreasing size of a small clam; that is, both present-day management and the 3-year closure option result in the landing of about the same number of clams per bushel when the definition of a small clam is 64 mm (Tables 2 and 4). In contrast, in all cases at the longer closure times of 5 and 7 years,

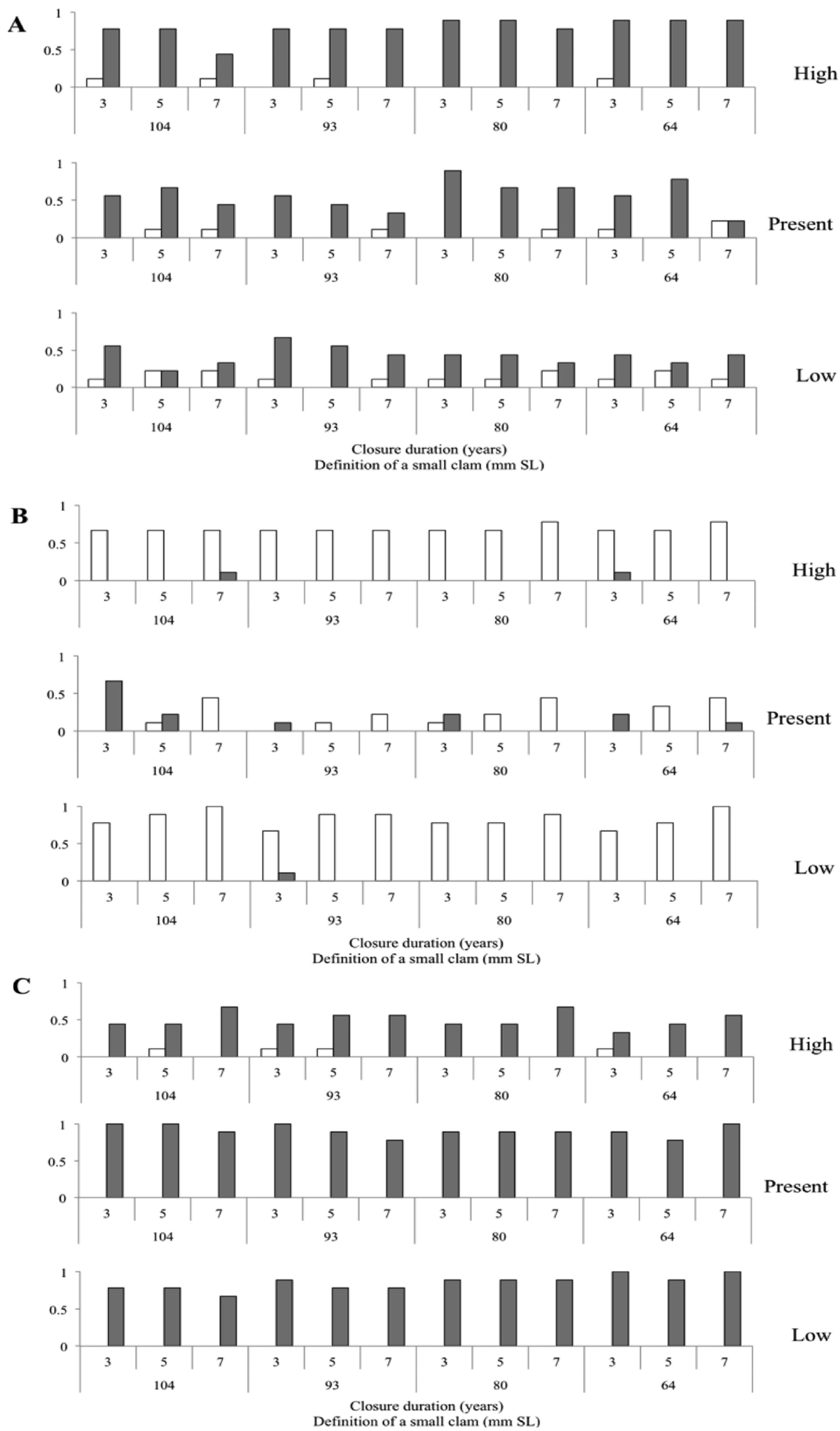

Fig. 7. The proportion of simulations where (A) landings per unit effort (LPUE), (B) the number of ten-minute squares (TMS) fished, and (C) the distance traveled when fishing were significantly higher using present-day or alternative management at high, present-day, and low abundance levels using closure location Rule 2 with 0% incidental mortality. Open bars represent the proportion of simulations where metrics were significantly greater using present-day management. Shaded bars represent the proportion of simulations where metrics were significantly greater using alternative management.

larger (and therefore fewer) clams were landed with the closure option in comparison to present-day management. When incidental mortality is increased from 0% to 20%, the effect of area management is most significant at low and present abundance (Tables 3 and 5). Alternative management consistently resulted in the landing of larger clams with increased incidental mortality, as it did with 0% incidental mortality at present-day abundance. The largest definition of a small clam (104 mm) resulted in the landing of larger clams regardless of the level of incidental mortality, but the differential between clam sizes was limited (Tables 4 and 5).

3.2.3. Landings per unit effort

As abundance increases, the proportions of simulations that show significant increases in LPUE using area management also increased (Fig. 7). At low abundance, the 3-year closure duration had the largest proportion of simulations (0.53) that showed a significant increase in LPUE averaged over all definitions of a small clam (Table 2). The average was underpinned by clear differences for cases where closures were based on clams 93–120 and 104–120 mm. At present-day and high abundance, the 3-and 5-year closure durations had the largest proportions of simulations that showed a significant increase in LPUE; the differential was clearest for present-day abundance (Table 2, Fig. 7). When incidental mortality is increased from 0% to 20%, the effect of area management is enhanced at low and high abundance, but interestingly, not at present-day abundance (Tables 3 and 5). At high abundance, the smallest definition of a small clam offers the most improvement to LPUE and as the abundance declines improvements increase with larger definitions of a small clam (Table 4). When incidental mortality is increased, the 80 mm and 64 mm definitions of a small clam outperform the larger definitions of a small clam (Table 5).

3.2.4. Number of ten-minute squares fished

Generally, more TMSs were visited when fishing using present-day management in comparison to area management at low and high abundance (Fig. 7). The effect of area management can be seen in the reduction in the number of TMSs fished. The reduction is not as substantial at present-day abundance, particularly with a 3-year closure (Table 2). When incidental mortality is increased, the overall trend of present-day management resulting in more TMSs being visited when fishing is enhanced, albeit modestly, particularly for the present-day abundance level (Tables 3 and 5). With a few exceptions, the number of TMSs fished normally is greater under present-day management regardless of the size of clam used for closure with or without incidental mortality (Tables 4 and 5).

3.2.5. Distance traveled per fishing trip

The distance traveled per fishing trip was normally greater using area management for all levels of abundance (Fig. 7). At high abundance, as the closure duration increases the proportion of simulations with increased distance traveled under area management also increases (Table 2). The differential between the proportion of simulations that showed increased distances using present-day and alternative management increases at lower abundances, including present-day abundance (Fig. 7). When incidental mortality is increased from 0% to 20%, the proportion of simulations with increased distance traveled during fishing under area management decreases, particularly for the present-day and high abundance cases, but area management still results in longer distances traveled overall (Tables 3 and 5). Little difference exists between the clam size options for closure overall in the tendency for travel distance to increase with area management (Tables 4 and 5) with or without incidental mortality.

4. Discussion

4.1. Perspective

The primary objective of this study was to carry out a MSE to investigate alternative area management options at varying stock abundances that could potentially provide insulation to the Atlantic surfclam stock and commercial fishery in the northeastern US from the detrimental effects of a contracting stock range resulting from climate change. The range of the surfclam stock is contracting and shifting to areas further away from active commercial ports in response to increased water temperature (Kuykendall et al., 2017; Hofmann et al., 2018). Due to the shifting and contracting range of the population, several ports that were once historically important for the surfclam fishery in the southernmost region have already closed. The range contraction of the surfclam population has also caused increased fishing pressure north of this region off New Jersey, a region historically already supporting a large (greater than 80%) proportion of the surfclam fishery, with consequences including declining LPUE in this region and an inability to meet quotas for the fishery as a whole.

The current FMP does not address the challenges of declining LPUE, inability to meet quotas, and regional increases in fishing pressure. New management options need to be considered. Marine protected areas (MPAs) have received considerable study. Permanent MPAs have been implemented for mobile species or for species living in gear-sensitive habitats (e.g., Nowlis, 2000; Chakraborty and Kar, 2012; Pinsky et al., 2012; Baskett and Barnett, 2015). For sessile species, temporary (rotational) closures are often employed. Area management via temporary closures was chosen as the alternative management option for study for two main reasons: (1) the documented success of management plans that employ regional rotational closures in improving other shellfish fisheries (Walters, 2000; Bloomfield et al., 2012; Córdova-Lepe et al., 2012; Cooley et al., 2015) and (2) the concerns raised about disease refugia and disease spread in high-density situations with relatively constrained larval sources and sinks (e.g., Stokesbury et al., 2007; Munroe et al., 2014). Focus was placed on improving performance metrics including enhancements to the stock and economic benefits to the commercial fishery.

The primary purpose of temporary closures is to protect areas where quantities of submarket-size clams are found, thereby permitting them to grow to market size without being impacted by fishing activities. Implementation of such a scheme requires answering three questions (Table 1). (1) How are sites to be chosen? In this study we examined two closure rules, one based on the proportion of small clams present and one based on the numbers of small clams present. (2) What size range of small clams should be chosen upon which to base this decision? In this study, we chose four size ranges defined by the number of years required by the smallest clam to grow to market size. (3) How long should the closure be? In this study, we considered 3-, 5-, and 7-year closures based on the fact that clams are in the 5–10 year range when they recruit to the fishery (NEFSC, 2017). Powell et al. (2015, 2016) examined the influence of varying proclivities inherent in how surfclam captains choose locations to fish and found that certain decisional tendencies substantively affected the resulting economic performance and also the impact on the stock. Such an outcome is not unexpected (Hilborn, 1992; Gillis et al., 1995; Millischer and Gascuel, 2006; Link et al., 2011). Thus, how captains might respond to temporary closures may considerably affect the efficacy of this management option. Consequently, captain behaviors were included in order to assess the response of the fishery to management (present-day and alternative) in the most realistic manner possible.

Kuykendall et al. (2017) used a MSE to examine the potential of temporary closures under present-day conditions. They found that closing areas based on the proportion of small clams present outperformed the alternative of closing areas based on the numbers of clams present. Additionally, they found that 5-year closures performed better than 3-year closures and that 7-year closures did not improve performance enough to warrant the additional two years of closure. In addition, they found that the smaller definitions of a small clam, particularly the 80–120 mm size class, was the most useful size class upon which to base a closure decision based on improvements in both stock density and LPUE using preferred closure location criteria.

The MSE model used by Kuykendall et al. (2017) (SEFES) captures many of the variable components of the surfclam stock and fishery such as varying growth, patchiness in distribution, and captain behaviors; however, Powell et al. (2015) showed that changing population dynamics may exert critical performance changes on the fishery and the record of the surfclam fishery over the last tricennial supports that conclusion (McCay et al., 2011; Hofmann et al., 2018). The thirty-year time series of stock abundance shows substantial variations with abundances higher than present-day routinely observed in the region of study prior to 2000 (NEFSC, 2013). The shift in range is not due to fishing pressure. Fishing mortality rates are well below the maximum sustainable yield reference point (NEFSC, 2017). Continuing warming of the Mid-Atlantic (Nixon et al., 2004; Friedland and Hare, 2007; Hare et al., 2016), however, engendering an anticipated further contraction in range portends a transient or permanent decrease in abundance. The present FMP cap being well below the overfishing limit (OFL), a substantial decline in abundance would not influence the present quota, but it would substantively impact the fishery, as captains have only limited ability to modify fishing performance to counterweigh an abundance-enforced decline in LPUE. Thus, an evaluation of an area management option must take into account potentially substantive changes in stock size. In this study, we compare management outcomes between present-day abundance and a decreased abundance to a level just above a level that would trigger a quota reduction (NEFSC, 2013) (low abundance level). Not knowing the potential for stock expansion over time, as the stock equilibrates to an expanded offshore and northern range, we also compare a higher abundance case to the present-day. Both comparisons permit evaluation of the long-term potential of area management during a time of anticipated rapidly changing stock abundances.

A further concern is the potential influence of incidental mortality of small surfclams as a consequence of fishing. The hydraulic dredges used in the surfclam fishery are highly efficient at capturing animals 120 + mm. Efficiencies typically exceed 70% (NEFSC, 2013) and are superior to the efficiencies of most shellfish dry dredges (e.g., Lasta and Iribarne, 1997; Beukers-Stewart et al., 2001; Powell et al., 2007). Smaller animals are disturbed: some are not caught; some are caught, but then discarded. High-grading does not occur in this fishery. Size sorting occurs on the bottom (dredge selectivity) and on the deck where a sorter is employed to remove single shells and shell fragments, perforce accompanied by a high percentage of the remaining submarket-size clams. Severe and often fatal shell damage can be incurred from fishing gear (Witbaard and Klein, 1994; Alexander and Dietl, 2001; Moschino et al., 2003; Gilkinson et al., 2005; Vasconcelos et al., 2010; Chandrapavan et al., 2012) and the resultant mortality can be difficult to measure. No data are presently available regarding incidental mortality of surfclams that are intercepted but not retained by a commercial dredge or discarded. To assess the potential impact of incidental mortality, two levels of incidental mortality were investigated, 0% and 20%, both arbitrary but perhaps encompassing a likely value (Table 1).

To restrict the range of the study, some constraints were imposed on the ambit of the simulations. Vessels and their technologies were held constant over the entire simulation time frame (76 years) because the advances in fishing gear and practices and the extent to which those advances will affect the fishery are unknown. Climate change likely will continue to affect bottom water temperatures (Scavia et al., 2002; Feely et al., 2009; Saba et al., 2016), and thus the range of the surfclam, but the impact of those changes on the Atlantic surfclam and its range in the foreseeable future are speculative. In order to maintain parsimony, climate change resulting in shifts in the species' range and consequent variations in growth and mortality rate (e.g., Narváez et al., 2015; Munroe et al., 2016; Hofmann et al., 2018; Powell et al., 2017) is not included in this study.

4.2. Area management: general influence of abundance

Variations in stock abundance dramatically influenced most performance metrics, whether descriptive of the stock or the fishery. Interestingly, these effects were not consistent across metrics. Certain performance metrics, such as distance traveled when fishing (Table 3) improved in performance when abundance was higher than present-day. In this case, the tendency for distance traveled to increase under area management was ameliorated. Certain performance metrics, such as stock density and LPUE (Table 3), improved in performance when abundance was lower than present-day. In these two cases, for example, area management increased LPUE and stock density more at low abundance than at high abundance. The increased stock density at low abundance in comparison to present-day management can be attributed to the protection of some portion of the stock, particularly the submarket sizes, within a closed TMS, along with the enhanced landing of large clams which results in fewer clams being removed from the stock per landed volume. The improvements seen in stock density and LPUE when abundance is low at both 0% and 20% incidental mortality demonstrate the positive influence of area management when conditions of the stock and fishery are at their worst (Tables 2 and 3). Effects of area management on performance metrics at present-day conditions typically fell in-between and were often less than observed in one of the other two abundance levels. A consequence of these trends is to introduce differential expectations of outcomes depending upon future conditions, and particularly such that the stock and the fishery are not on parallel tracks with respect to them.

4.3. Area management influence on the *Spisula solidissima* stock

Stock density measured as the density of clams ≥120 mm shell length per square meter and the number of clams per bushel were used to evaluate the effects of area management on the *S. solidissima* stock. Simulations suggest that closure Rule 1 offers the most benefit to the stock. Using Rule 1 resulted in more simulations with increases in fishable-stock density in comparison to the absence of closures (present-day management) (Table 3). At low abundance when stock density is of greatest concern, simulations resulted in stock density increases in a larger proportion of simulations for all closure durations using Rule 1 in comparison to Rule 2 (Table 3). Additionally, the proportion of simulations showing increases in stock density at low abundance (the most dire situation) for the shortest closure duration using Rule 1 is nearly equivalent to the improvements seen with high abundance (most ideal situation) and the longest closure duration using Rule 2.

Stock density was positively influenced more often at low abundance than at high abundance. Under Rule 1, the difference was often more than double (Table 3). Thus, the positive effects of temporary closures on the stock are specifically most enhanced at stock densities where they are most needed. An additional metric to evaluate the status of the stock is to monitor the size of landed clams measured in this study as the number of clams per bushel. This metric provides one explanation for the trends across abundance levels. As the size of a clam increases, fewer individuals are needed to fill a bushel. As the commercial fishery quotas are based on volume, when fewer clams are required to fill a bushel, fewer clams are removed each fishing trip from the stock. At low abundance, larger clams are consistently landed under area management. At high abundance, the tendency towards the landing of larger clams is muted, though still present (Table 3). The increase in the size of landed clams under area management shows that closing an area for a number of years (i.e., protecting TMSs where small clams are dominant) permits clams to grow to a larger size unhindered by the fishery, whereupon when opened, this location provides a disproportionate part of the catch, thereby permitting clams elsewhere to also grow to a larger size. As a consequence, stock density is enhanced and because the fishery concentrates more on recently-opened areas when abundances are low, enhancement of stock density is greater when abundances are low.

The MSE model does not include a density effect on fecundity beyond a standard compensatory broodstock-recruitment curve. The number and density of patches is enhanced by area closures as is revealed by the positive influence of closures on. Depensation, though uncommon in finfish (Myers et al., 1995), may be of greater consequence in shellfish because shellfish have low mobility; thus increased patch number or density may also enhance recruitment (Peterson et al., 1996; Tettelbach et al., 2013; Munroe et al., 2018). A density effect on fertilization success is not included in the model, however, although it is well described for broadcast–spawning sessile and sedentary marine invertebrates (Levitan, 1991; Babcock et al., 1994; Gaylord, 2008), because the specific density relationships are unknown for surfclams. Thus, the positive influence of temporary closures on surfclam stock density observed in this study likely underestimates the results that might be anticipated.

4.4. Area management influence on the commercial fishery

Three performance metrics, LPUE (bu h^{-1}), the number of TMSs fished, and the distance traveled during fishing (km), were used to evaluate the effects of area management on the commercial fishery. LPUE rises under area management consistently more under conditions of high abundance compared to low abundance. At high abundance, the proportion of simulations with improved LPUE for both Rule 1 and 2 are greater than 70% (Table 3). LPUE increases due to the higher abundance per se, but this effect is equivalent for cases with and without temporary closures. The positive influence of temporary closures on LPUE at high abundance occurs despite the lesser effect of area management on stock density at high abundance. This emphasizes the importance of patch density inside closed areas, which inherently will be higher at high stock abundance. The proportions of simulations that show increases in LPUE are very similar for Rule 1 and 2 at high abundance and present-day abundance (Table 3). Trends are less clear at low abundance, however clear enhancement occurs with a 5-year closure. Although the proportions of simulations that show improved LPUE are comparable between Rule 1 and Rule 2 for high and present-day abundance levels, Rule 1 outperforms Rule 2 when the abundance is low for the 5-year closure (Table 3). The improvement of LPUE at low abundances is most desirable by the commercial fishery in order to best insulate the fishery from anticipated stock declines as the range shifts north and offshore in response to warming bottom water temperatures. Thus, the distinct advantage shown at low abundance for the 5-year closure under Rule 1 is consequential.

The number of TMSs fished is greatly reduced using area management, particularly when using closure location Rule 1. Captains target recently opened TMSs that produce larger LPUEs consequently decreasing the number of TMSs fished. Release of fishing effort elsewhere is one factor supporting enhanced stock density. Furthermore, Rule 1 produces greater LPUEs in recently opened squares than Rule 2, as shown by the lack of simulations where more TMSs are fished using Rule 1 (Table 3). This provides one reason for the tendency for Rule 1 management to enhance stock density more than Rule 2 management. That is, more simulations showed more TMSs being fished using Rule 2 in comparison to Rule 1.

Additionally, the increase in distance traveled when fishing under area management is almost always less using Rule 1, and particularly so at present-day and low abundance when the effects of area management are most important. This is consistent also with the fewer TMSs fished. A decrease in distance traveled is desirable by the commercial fishery in order to reduce operational costs (i.e., fuel) and to provide more time fishing within the 36–48-hr window to complete a typical trip. An increase in distance traveled is expected as the closure duration increases because a larger portion of the fishable area is closed including TMSs nearer port regardless of the closure location rule. This trend is clearly seen at all abundance levels for Rule 1, but only at high abundance for Rule 2.

4.5. Influence of control rules

The increased travel time is a principal reason to limit closures to no more than 5 years and to focus on Rule 1 as the closure rule. Rule 1 closes an area based on the proportion of clams of submarket size. Rule 1 resulted in improvements in most performance metrics (Table 5). Rule 1 resulted in the largest number of scenarios (i.e., combination of closure duration and abundance level) where stock density was greater using alternative management (Table 5). Larger clams were landed more often when using Rule 1 as shown by Rule 2 resulting in a greater number of clams per bushel in more scenarios (Table 5). LPUE is the only metric where Rule 2 had a greater number of scenarios with larger proportions of simulations showing improvements. However, the differential was primarily present at low abundance and was reversed when the 5-year closure duration was used (Table 3). Rule 2 resulted in a greater number of TMSs being fished in more scenarios than Rule 1 (Table 5). An increase in the number of TMSs fished is consistent with the increased distance traveled during fishing using Rule 2 (Table 5). Finally, these trends were consistent across abundance levels. That is, the tendency for Rule 1 and a 5-year closure to outperform other options was true at high, present-day, and low abundance, even though the most impacted performance metrics varied across these abundance levels.

Rule 2 depends solely on the number of small clams in a TMS. Rule 1 results in a closure choice biased in favor of small clams, but also biased against larger clams. This differential bias provides the basis for the improved performance of Rule 1 relative to Rule 2. The targeting of larger clams by the fishery inherently minimizes the influence of a given quota on the entire stock. Fewer clams are landed to fill the same volume. Rule 1, by tending to permit TMSs with many large clams to remain open to fishing, focuses the fishery on the size classes most economical to the stock and, accordingly, Rule 1 outperforms Rule 2 in most area management comparisons.

4.6. Influence of incidental mortality

Although most market-size clams that encounter the fishing gear are retained and landed (Hennen et al., 2012), the impact of fishing gear on smaller individuals is still unquantified. Some small clams are resuspended, but not retained in the dredge. Others are caught, but then discarded by the onboard size-sorting equipment. Increasing incidental mortality of clams that encounter the dredge but are not landed from 0% to 20% enhanced the effect of area management on all performance metrics consistently at most closure durations regardless of the closure location rule or abundance level (Tables 3 and 5). Thus, the assumption of no incidental mortality provides a minimal estimate of the positive influence of temporary closures.

The improvement in performance metrics when incidental mortality is increased can be attributed to the protection from incidental mortality that an area closure can provide. Using present-day management and increased mortality, the entire population is subjected to an increase in mortality in comparison to area management where some proportion of the population is protected at any given time from the additional mortality. Moreover, when these closed areas are opened, fishing effort transfers to regions of relatively high market-size abundance, thus partially protecting smaller clams throughout the remainder of the resource.

The greatest effect of increasing incidental mortality is seen at low abundance. Generally, the positive effect of area management with increased incidental mortality also occurs at the two higher abundance levels, but primarily at the longer closure durations. Reference to the effect of closure time as it interacts with the definition of a small clam (e.g., Tables 3 and 5) shows that cases where area management did not substantively improve stock density with higher incidental mortality occurred at the 3-year closure when the closure rule was based on 64-mm and sometimes 80-mm clams. For these small clams, the time needed to grow to market size exceeds the duration of the area closure. Thus, if area management only protects the small clams for 3 years, these clams are subjected to additional mortality for the remaining 2 years prior to reaching market size during which time dredge selectivity remains low; that is, many are intersected by the dredge, but not landed.

LPUE is increased consistently when incidental mortality is increased using Rule 1 (Tables 2–5) in comparison to present-day management and to alternative management using Rule 2. Although the differential between incidental mortality levels is not as great when using Rule 2, the proportion of simulations that show increases in LPUE was greater when incidental mortality was increased (Tables 2–5). The positive impact on LPUE was demonstrably greater at low abundance than at the other abundance levels. The number of TMSs fished is almost always greater using present day management and increasing incidental mortality had little to no effect on the number of TMSs fished regardless of the closure location rule (Tables 2–5). Some slight differences in the distance traveled when fishing can be seen, but in a majority of simulations little difference in the distance traveled was observed between the two levels of incidental mortality (Tables 2–5). When it was present, however, the distance traveled was reduced under the 20% mortality assumption in comparison to 0% and this is consistent with the higher LPUEs observed. Thus area management has an increased beneficial effect on the fishery with increased incidental mortality as it did on the stock.

The lessening effect of area management with increased incidental mortality at high abundance is best understood by the fact that the simulations were conducted under an FMP quota cap, the consequence of which is that the fishing mortality rate declines as abundance is increased. Thus, the impact of the fishery on small clams is limited at high abundance and consequently the benefit of area management is limited. The fact that clear improvement was observed under present day abundance, albeit less than in the low abundance case, however, suggests that incidental mortality may be an important but poorly documented impact on the stock and fishery today. Moreover, the positive impact at low abundance suggests that any adjustment to the FMP that would permit scaling of the quota relative to stock abundance would expand the positive impact of area management across a range of abundance levels.

4.7. Preferred management options

Based on the improvement of performance metrics in comparison to the case of present-day management without temporary closures and the alternative area management under closure location Rule 2, area management under closure Rule 1 is the preferred option regardless of the level of incidental mortality (Tables 5 and 6). The largest effects of alternative management under the preferred closure location rule (Rule 1) are seen in stock abundance and LPUE at low abundance. As abundance decreases, the proportion of simulations that report a higher stock density in comparison to present-day management increases (Fig. 6). The proportion of cases with increased LPUE is lowest in comparison to present-day management when abundance is low (Fig. 6); however, the proportion of simulations with increased LPUE at low levels of abundance using the 5-year closure duration is comparable to the proportion obtained using present abundance with the same closure duration. Using Rule 1 at low abundance also resulted in more simulations with increased LPUE when incidental mortality is increased in comparison to Rule 2 (Tables 3 and 5). Being able to produce simulations where there are increases in LPUE and stock density, particularly when stock abundance is lower than present-day abundance, provides support that long-term sustainability (i.e. fishery viability) can be achieved with proper management plans. Area management varies outcomes less at high abundance, but gains in LPUE remain important and the positive response in stock density and LPUE under conditions of increased incidental mortality remain clear.

Table 6
A comparison of Rule 1 and Rule 2 based on the number of scenarios (i.e., combination of closure duration and abundance level) that resulted in larger values for performance metrics in a greater proportion of simulations. A black plus sign represents a higher value of the performance metric that is a positive outcome for the fishery or the stock (i.e., Rule 1 had a larger value for the performance metric measuring stock density and a smaller value for the metric measuring the number of clams per bushel). A black plus-minus sign represents a higher value of the performance metric that is a negative outcome for the fishery or the stock.

Performance Metric	Incidental Mortality			
	0%		20%	
	Closure Rule			
	1	2	1	2
Stock Density	+		+	
Number of Clams Per Bushel		±	±	
LPUE		+	+	
Number of TMSs Fished		±		±
Distance Traveled During Fishing		±		±

The 5-year closure option performs best. A 3-year closure performs poorly for many performance metrics and a 7-year closure rarely accrues a result substantively beyond the 5-year case (Fig. 6). The intermediate size classes (80–120 mm and 93–120 mm) tended to performed better than the other definitions of a small clam (Table 4), but the interaction between closure durations and the number of years required to grow to market size was important. The 5-year closure often balances a preference in one metric for a 3-year option relative to a preference for another metric for a 7-year option. The same is often true for the intermediate size classes. Of note, this balancing is a particularly strong characteristic when abundances are low. Closure durations are relatively inconsequential at high abundance.

What is interesting is the positive influence of area management across a wide range of stock abundances. Certain performance metrics are more beneficial under certain abundance regimes than others, but an overall positive influence remains regardless of abundance. Thus, the status of the stock exerts little influence in the decision to invoke temporary closures, except, perhaps, in the degree of improvement relative to the cost of implementation. That cost has not been considered in this study. However, the fact that outcomes are particularly positive at low abundance is important for two reasons. Economics of the surfclam fishery are particularly impacted by low abundance because patches that can sustain a minimally required LPUE are limited and captains have little ability to ameliorate this impact (Powell et al., 2016). In addition, although the influence of low abundance on surfclam population dynamics is unknown, the fact that sedentary species often have limited ability to rebuild from low abundance (Peterson, 2002; Kraeuter et al., 2008; Levitan et al., 2014; Tettelbach et al., 2013) recommends management measures that would facilitate that outcome.

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