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Captains' response to a declining stock as anticipated in the surfclam (*Spisula solidissima*) fishery on the U.S. Mid-Atlantic coast by model evaluation

Eric N. Powell [a,*], John M. Klinck [b], Eileen E. Hofmann [b], Paula Moreno [a], Kelsey M. Kuykendall [a], Daphne M. Munroe [c], Roger Mann [d]

[a] Gulf Coast Research Laboratory, University of Southern Mississippi, 703 E. Beach Dr., Ocean Springs, MS, 39564, United States
[b] Center for Coastal Physical Oceanography, Department of Ocean, Earth and Atmospheric Sciences, 4111 Monarch Way, 3rd Floor, Old Dominion University, Norfolk, VA, 23529, United States
[c] Haskin Shellfish Research Laboratory, Rutgers University, 6959 Miller Ave., Port Norris, NJ, 08349, United States
[d] Virginia Institute of Marine Science, College of William and Mary, P.O. Box 1346, Gloucester Point, VA, 23062, United States

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A B S T R A C T

Mid-Atlantic Bight (MAB) warming accompanied by a decline in recruitment has slowly reduced surfclam abundance. Simulations examined fishery dynamics during an extended period of low recruitment followed by stock recovery after a high-recruitment event. The model assigned performance characteristics to each vessel and gave captains defined behavioral proclivities including a tendency to search, to communicate with other captains, to use survey data, and to integrate variable lengths of past-history performance in targeting fishing trips. During the simulated excursion in abundance, LPUE (landings per unit effort) declined as lower abundance required an extended time at sea to catch a full load. Captains expanded their geographic range of interest steaming farther from port in an effort to maintain their performance. Net revenue declined. Use of survey data significantly improved performance. About equal in positive effect was moderate searching. Other behaviors incurred penalties. Communication failed to improve performance because both poor and good information was transferred. Reliance on a long period of catch history failed to improve performance because information was out of date during a time of rapidly changing conditions. In these simulations, no captains' behaviors prevented a collapse in vessel economics at low abundance, but certain behaviors limited the degree and duration of economic dislocation.

1. Introduction

The Atlantic surfclam, *Spisula solidissima*, sustains one of the largest shellfish fisheries on the east coast of the U.S. Since the early 1990s, the fishery has operated under a specified quota distributed to shareholders under an ITQ (individual transferable quota) system (Adelaja et al., 1998; Chu, 2009; McCay et al., 2011). During the years subsequent to the initiation of ITQ management, the fishery has operated at a fishing mortality rate well below the natural mortality rate and well below the management reference point proxy for F_{msy} (NEFSC, 2013). During this time, the stock has remained above the biological reference point proxy for B_{msy} (NEFSC, 2013). As a consequence, the fishery has generated only limited management concerns.

Surfclams, however, are sensitive to bottom water temperatures above about 21 °C (Weinberg, 2005; Munroe et al., 2013) and large animals are sensitive to variations in food supply (Kim and Powell, 2004; Munroe et al., 2013). As a consequence, warming of the Mid-Atlantic Bight (Scavia et al., 2002; Jossi and Benway, 2003; Friedland and Hare, 2007), likely accompanied by a reduction in food supply (Xu et al., 2011), has resulted in a contraction of range for this species since the mid-1990s (Weinberg et al., 2002, 2005; Weinberg, 2005) characterized by a large-spatial-scale mortality event at the southern boundary of the range (Kim and Powell, 2004) driving the southern boundary northward and the inshore boundary offshore. A compensatory range expansion anticipated

* Corresponding author.
E-mail address: eric.n.powell@usm.edu (E.N. Powell).

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off Long Island has not occurred, although the modest offshore range extension off New Jersey is well-documented (e.g., Weinberg et al., 2005). Obvious impacts on the fishery from this range shift became apparent by the mid-2000s and include the movement of processing capacity northward, the shift of vessels from southerly ports northward, the focus of heaviest fishing pressure in a smaller region of the MAB, and the re-opening of the fishery on Georges Bank which had been closed for many years due to PSP (paralytic shellfish poisoning) concerns (Magnuson-Stevens Fishery Conservation and Management Act, 2012). Nevertheless, one consequence of the post-1990 warming episode is a contraction of the region supporting much of the fishery east and south of Rhode Island from the original southerly extent off Maryland and Virginia extending to northern New Jersey to a primary focus in the northerly region off New Jersey (NEFSC, 2013).

Because the fishery has operated under a cushion provided by a stock size well above B_{msy} and a fishing mortality rate well below F_{msy}, the stock contraction has not imposed stringent demands on management of the fishery, although it has imposed costs to the industry in relocating fishing effort. However, the reduced areal extent of the fishery has resulted in concentrated effort off of New Jersey, where locally fishing mortality rates have risen and LPUEs (landings per unit effort) have declined. In addition, recruitment in this region has been low for the last decade, so that the biomass of harvestable clams has dropped more or less consistently since 1997. These dynamics, both economic, managerial, and biological, influenced the development of a management strategy evaluation (MSE) model of the surfclam industry (Powell et al., 2015; see Spillman et al., 2009; Baudron et al., 2010; Bastardie et al., 2010; Miller et al., 2010 for other examples of MSE models). Powell et al. (2015) examined the importance of behavioral choices made by captains under conditions that existed during the 1990s and under the more difficult conditions of the 2000s. The approach to fishing implemented by the vessel captains is an important ingredient in the dynamic of any fishing industry (Dorn, 1998, 2001; Gillis et al., 1995a,b; Powell et al., 2003a,b). How these choices interact with changing dynamics of the stock and differences in fishing vessel size represent both an important component of the economic response by the fishery (Lipton and Strand, 1992) and an important component of an MSE.

Powell et al. (2015) examined the influence of the captain's approach to fishing during a period of climate change that resulted in contraction of the stock and concentration of the fishery. They found that the repertoire of behavioral options did not substantively influence the primary metrics influencing the outcome of a fishing trip, such as LPUE. This outcome agreed with responses from interviews with surfclam vessel captains who indicated only limited variation in the approach to fishing between the 1990s and 2000s. Thus regional changes in stock distribution would appear to challenge captains skill relatively little. However, the examination by Powell et al. (2015) presumed that the contraction of the stock did not materially affect stock abundance available to the fishery, an assumption that was reasonable given the history of climate change and of the surfclam stock in the early 2000s, but which may no longer be a valid assumption in the 2010s because accompanying these changes in stock distribution has been a decline in recruitment that has slowly reduced the abundance of the MAB stock.

The purpose of this contribution is to utilize a MSE model to investigate how ongoing stock reductions if continued over another decade may influence the surfclam fishery as modulated through the ambit of choices available to the vessel captains as they execute their fishing trips. The study focuses on fishery performance as defined by metrics such as LPUE, vessel economics as influenced by fuel usage and landings per trip, and fleet dispersion, as declining stock biomass in the MAB influences the fishery long before it triggers quota reductions under present-day management guidelines.

2. The model - SEFES (Spatially-explicit fishery economics simulator)

2.1. Overview

SEFES is a model capable of simulating a spatially and temporally variable resource (in this case, surfclams) harvested by fleets of boats landing in a number of homeports. The structure of SEFES is depicted in Fig. 1 and described in detail by Powell et al. (2015). The following summarizes that description. Boats and processing plants are the active agents in the model. The boats are attached to specific processing plants and land catch at dedicated ports. The boat may have varying characteristics such as different speeds, harvest capacities, and costs. Each boat is controlled by a captain with specified characteristics that determine where and how efficiently the boat harvests the resource. Boats move around the domain and harvest clams based on decisions by the captain and constrained by the operating characteristics of the boat, such as speed, maximum allowed time at sea, and imposed harvest quota. Each port has a processing plant that purchases the harvested clams, providing income for the boats, and distributes quota obtained from the ITQ holders to each boat on a weekly schedule. This top-down control of fishing effort expresses present-day operational practice in the fishery.

The spatial domain is partitioned into rectangular cells ten minutes on a side. Within each cell, the clam population is described in terms of clams m^{-2} per 1-cm size class. The number and size distribution of clams varies over time in response to different biological and fishery processes. Surveys are conducted annually. A management module sets the harvest quota for the next year. The basic units in the model are SI (Système international d'unités) with time in seconds, distance in meters, and weight in kilograms. For convenience, commonly-used units are employed for some characteristics, such as specifying boat speed in knots (kt).

2.2. Domain and geometry configuration

The domain investigated in this paper is the MAB off the east coast of the US. The east-west extent of the domain has 17 cells across-shelf in the south and alongshore in the north to represent the transition from a quasi north-south trending shoreline south of Hudson Canyon to an east-west shoreline north of it. The north-south extent of the domain has 26 cells from Long Island south. For convenience, this model domain has the MAB rotated slightly counterclockwise to remove the northeastward trend south of Long Island, but this slight distortion of the domain has a negligible effect on model processes.

A mask is imposed on the model domain which identifies each cell as land, water uninhabited by surfclams, or water inhabited by surfclams. This mask is static, being defined at the beginning of a simulation. Ports are specified in certain land cells. For the simulations in this paper, three ports are included: Ocean City, Maryland; Atlantic City, New Jersey; and Pt. Pleasant, New Jersey (Fig. 2). At present, Atlantic City and Pt. Pleasant account for most of the landings (NEFSC, 2013) exclusive of the southern New England fishery off Nantucket and on Georges Bank.

2.3. Boat details

2.3.1. Operating characteristics

Vessel characteristics were obtained from interviews in 2012 with industry representatives and boat owners and operators.

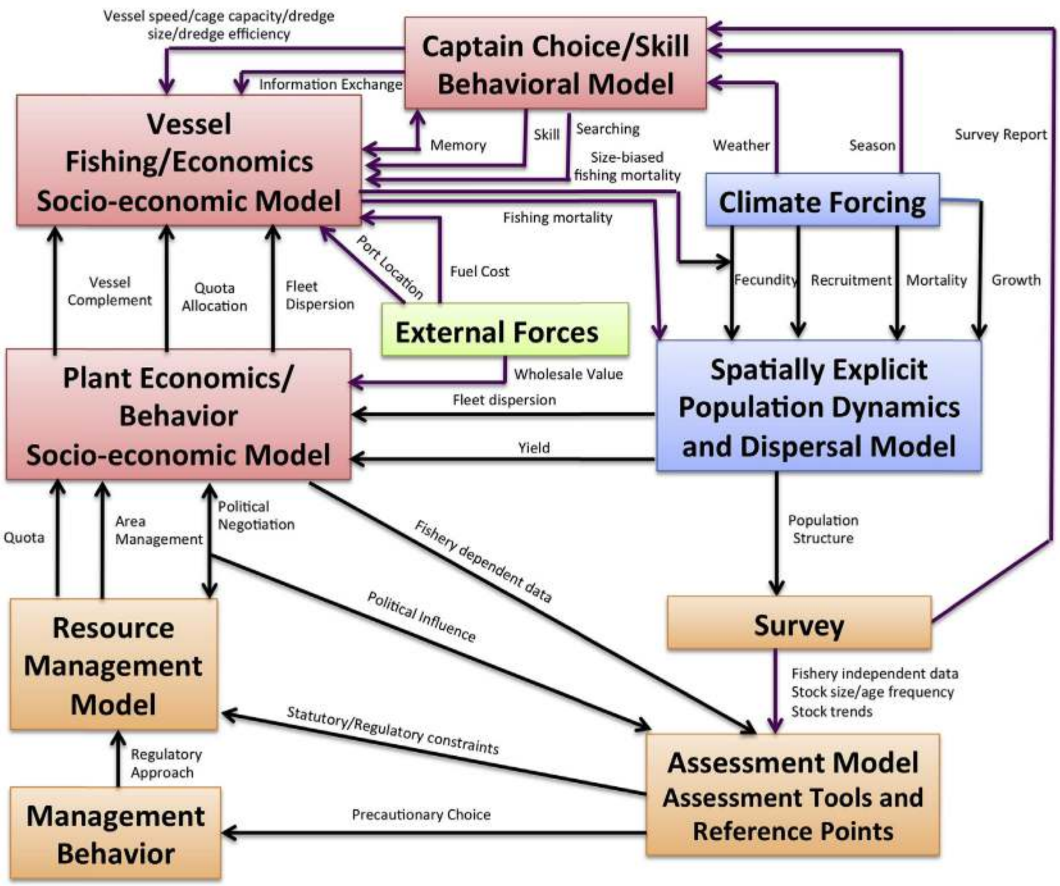

Fig. 1. SEFES model structure showing population dynamics components in blue, survey and management components in orange, external forces in green, and industry structure and function in pink.

Although a spectrum of detailed differences exist among vessels in the surfclam fleet, these vessels can be grouped crudely into small (~40-cage capacity),[1] medium (~80-cage capacity), large (~120-cage capacity), and jumbo (~160-cage capacity). For this study, two common vessel types were compared: small and large. The large vessel has 3 times the capacity of the small vessel. To maintain fishing power equivalent, simulations with small vessels included three times as many vessels as simulations with large vessels. To obtain fishing mortality rates representative of that observed in today's fishery in the MAB, simulations included either 15 large vessels, five per port, or 45 small vessels, 15 per port. Each boat in the model has the following characteristics specified: for the small vessel, steaming speed, 8 kt; maximum on-deck processing capacity, 6 cages hr^{-1}; dredge width, 2.6 m; dredging speed, 3 kt: for the large vessel, steaming speed, 12 kt; maximum on-deck processing capacity, 20 cages hr^{-1}; dredge width, 3.8 m; dredging speed, 3 kt.

2.3.2. Boat economics

Vessel economic data came from MAFMC (1988; see also Weninger and Strand, 2003) as updated by interviews in 2012 with industry representatives and vessel operators. For these simulations, the following were specified (small vessel, large vessel): fixed costs (\$1579 d^{-1}, \$1165 d^{-1}); crew share as fraction of catch revenue (0.2, 0.2); boat share as fraction of catch revenue (0.15, 0.15); gear maintenance (\$1500 trip^{-1}, \$1000 trip^{-1}); fuel use steaming (30 gal hr^{-1}, 50 gal hr^{-1}); fuel use fishing (45 gal hr^{-1}, 80 gal hr^{-1}). The higher fuel use while fishing occurs because these vessels use hydraulic dredges and the water pump is engaged while dredging. Higher fixed costs and costs of gear maintenance for the smaller vessels incorporate the average older age of the vessel in service. For these simulations, the ex-vessel value of landings was set at \$12 surfclam bu^{-1} and the price of fuel was set at \$4 gal^{-1}. As many of the economic values used are temporally variable and as the tight relationship between plant and vessel minimizes the requirement for positive net vessel revenue, economic results are best assessed on a relative basis by comparing outcomes between ports, vessel sizes, and captains.

2.4. Captain descriptors

Information describing a captain's decision-making process when planning a fishing trip, constraints imposed by dealer landing deadlines, and the captain's approach to information acquisition on surfclam abundance came from interviews of vessel captains supplemented by interviews with other industry representatives and the authors' own extensive experiences.

2.4.1. Captain's memory

The captain controls where the boat fishes. Each captain retains the memory of past fishing trips. This memory includes an expected LPUE specified in cages per hour fishing for every fishable 10-min square in the domain. At the beginning of the simulation, the memory of each captain contains the LPUE that would be experienced by his boat for all 10-min squares based on initial surfclam

[1] 1 cage = 32 surfclam bushels = 1.7 m^3; 1 surfclam bushel = 53 L.

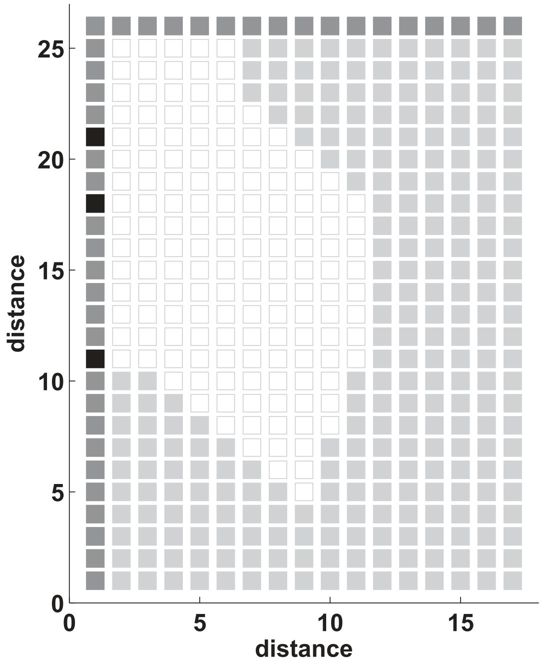

Fig. 2. The domain used to simulate conditions present during the 2000s. Black squares show the position of 3 ports, from north to south Pt. Pleasant, New Jersey; Atlantic City, New Jersey; and Ocean City, Maryland. Dark gray squares identify the remainder of the coast line. Light gray squares identify locations where surfclams are not found. The fishable domain encompasses the open squares. Note that the domain has been rotated for convenience to remove the northeast-southwest trend of the U.S. east coast south of Long Island without changing the dimensions of the 10-min squares or the distances between ports and fishing grounds.

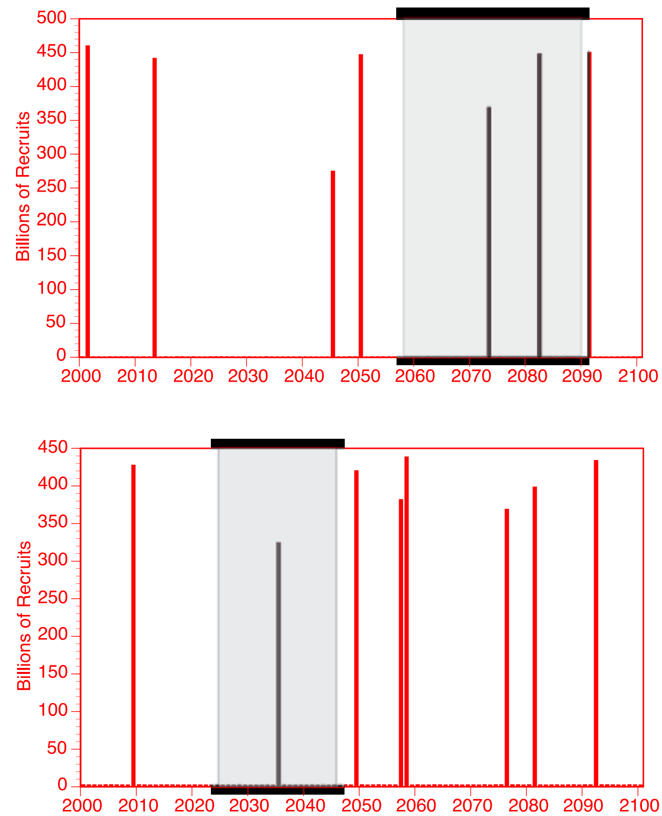

Fig. 3. Recruitment time series for the two case histories. Shaded region identifies the time frame used for statistical analysis and time series plots of fishing performance. The case shown in the upper plot is referred to in the text as Case 2. The lower plot is referred to as Case 1. Simulations were run for 100 fishing years arbitrarily designated to begin in 2000. The first 25 years were ignored (see Methods). The x-axis records the years since 2000. Thus Case 2 as extracted from the simulation time series represented years 58–90 of the 100-year simulation.

abundance. That is, initially, all captains have omniscient information. At the end of each fishing trip, the captain's catch history is updated for that 10-min square. In this way the captain's memory of the entire domain degrades over time as the surfclam population changes independently of the captain's experience and, therefore, updated memory of it. The captain uses his memory of LPUE to choose a 10-min square for fishing.

After fishing in a selected 10-min square and returning to port, the LPUE for that trip is used to update the information in the captain's memory based on a memory factor (*f*) that is a fraction indicating the weight placed on past information. If the fraction is 0.5, then the memory retained is the average of the previously stored and just obtained LPUEs. If the fraction is 1, then old information is retained and new information is ignored. If the fraction is 0, then old information is forgotten. For simulations discussed here, captains were assigned memory weights of 0.2 and 0.8 or 0.98 and 0.99 (see Fig. 3 in Powell et al., 2015). Thus, certain captains' memories were biased towards new or old information, respectively. Responsive captains, given a memory weight of 0.2 or 0.8, based fishing decisions on performance within the previous 1–6 weeks depending on the value of *f* and the number of trips taken per week. Obdurate captains, given a memory weight of 0.98 or 0.99, based fishing decisions on performance over a much longer period of time (7 months to well over 1 year). The responsive captain is considered an average captain in today's fleet and is used subsequently as a point of comparison to captains exercising alternative behaviors. Longer-term memory of locations with high numbers of seed clams that might provide fishing opportunities 4–6 years hence were not retained; rather, this information was conflated with the provision of survey data to selected captains as described subsequently.

2.4.2. Captain's idiosyncrasies

The captain is conferred certain degrees of boldness, inquisitiveness, and loquacity as summarized in Table 2. Specifics on implementation are provided in Powell et al. (2015).

Boldness determines if the captain's behavior includes searching. A timid captain never searches, a bold captain searches 40% of the time he leaves port, whilst the confident captain searches 20% of the time, about one to two times a month depending on the number of fishing trips. When searching, the captain targets a random square within a 6-hr steam of the homeport regardless of his memory of past LPUE performance in that square.

Inquisitiveness indicates whether or not a captain uses the most recent survey results to update his knowledge of the expected LPUE for each 10-min square. Indifferent captains do not use survey results, whereas inquisitive captains use the most recent survey. The federal surfclam survey occurs once every 3 years (NEFSC, 2013) and the provision of survey data to the public in the form of fishermen's reports (e.g., NEFSC, 1999; NEFSC, 2002) occurs within a few months of the survey. Thus, in these simulations, the inquisitive captain updates his memory every third year based on survey results.

Loquacity determines the tendency for a captain to share the results of his most recent trip with other captains. This propensity is invoked in the model in probabilistic terms. Captains are either taciturn, so that information is never shared, or loquacious, so that the captain shares information with each other captain with a probability of 0.5.

Simulations were run with captains varying by only one trait relative to the standard, responsive captain. Thus, the responsive captain is responsive, timid, indifferent, and taciturn (Table 2). In contrast, the confident captain varies from this suite of traits in only one way, he is confident rather than timid; in other words, he searches occasionally (Table 2). Similarly, the loquacious captain is identical to the responsive captain in all but one trait; he is loquacious rather than taciturn.

2.5. Processing plant

The harvest quota for the year is calculated based on the survey of the previous year and is distributed among the processing plants in proportion to the fraction of the total fishing power represented by the fleet attached to that plant. Each plant distributes quota to its fishing boats in proportion to their hold size on a weekly basis. The weekly quota for a boat is limited to twice its hold size to limit fishing trips to no more than twice a week. This is consistent with standard operating procedure in the surfclam fishery.

If the weekly quota for a boat averaged over the year is below twice its hold size, then the boat cannot complete two trips per week over the entire year. In this case, the quota is adjusted so that trips are more frequent when meat yield is highest. Depending on the success of the fishing effort, unused quota may accrue. At the beginning of each week, the unused quota for a plant is distributed proportionally to all boats attached to that plant. If the original quota cannot sustain two trips and the added quota is sufficient to support a second trip, a second trip is added. In no case does a third trip occur; rather, unused quota cascades down the following weeks until a one-trip week can be converted to a two-trip week.

2.6. Weather

Fishing may cease due to inclement weather, primarily in the winter. Thus, weather was imposed as a factor for 6 months of the year (October–March). The frequency of different winter wind speeds was obtained from two NOAA meteorological buoys (NDBC 44008 over Nantucket Shoals and NDBC 44009 off Cape May). This wind analysis gave the fraction of time that boats of different sizes could fish. For this study, during the winter, small boats have a 50% chance on any given day of leaving port; large boats have an 85% chance.

2.7. Surfclam biology

The initial clam distribution (clams m^{-2} per size class) is imposed by assigning a biomass for the total population as an initial condition. This biomass is distributed among 10-min squares as a total clam density (summed over sizes) using a negative binomial random distribution to create a patchy distribution over the cells in which clams can exist. Then, a spatially-varying size distribution is used to distribute the clams in each cell into size categories. The initial conditions are adjusted by running the model for 100 years without fishing, about three times the longest surfclam life span (Munroe et al., 2016), to allow the initial population to adjust to the chosen rates of growth, mortality, and reproduction. Fishing in each simulation, therefore, begins with a virgin stock.

The allometric relationship between length and weight was obtained from Marzec et al. (2010). The von-Bertalanffy growth parameters were estimated from information provided by the federal surfclam survey (Munroe et al., 2016; NEFSC, 2013; see also Munroe et al., 2013). Natural mortality is imposed once yearly using a specified instantaneous mortality rate that is the same across all size classes. Munroe et al. (2013) raise the issue of increased mortality at old age, consistent with other bivalves (see Powell et al., 2012). However, the presently-accepted stock assessment model retains the constant mortality assumption consistent with Weinberg (1999). Powell et al. (2015) provide the parameterizations.

Growth and mortality are varied by 10-min square by specifying the values of the von-Bertalanffy parameters k and L_∞, and the natural mortality rate at the corners of the domain and assigning values to each cell by interpolation. This permits latitudinal and cross-shelf variations in growth and mortality (Weinberg, 1999; Chintala and Grassle, 2001; Weinberg et al., 2002; Munroe et al., 2013, 2016). For this study, mortality rate was specified to increase from northeast to southwest across the domain to reduce surfclam abundance at the southern and inshore extremes of the range, consistent with Weinberg (1999, 2005). The von-Bertalanffy k varies latitudinally in the MAB from 0.25 yr^{-1} in the south to 0.19 yr^{-1} in the north and declines offshore to 0.15 yr^{-1}. L_∞ varies latitudinally from 150 to 164 cm.

Clams recruit to the population one day per year, chosen arbitrarily to be October 1. A stock-recruit relationship could not be resolved by the most recent stock assessment (NEFSC, 2013). Accordingly, for this model, Beverton-Holt parameters were estimated for the simulated virgin stock from an input value for steepness, set at 0.8 for these simulations, following the method of Myers et al. (1999; see also O'Leary et al., 2011). Each year, total recruitment, calculated using the Beverton-Holt relationship, is parsed out to each 10-min square by adding individuals to the smallest size class (20 mm) based on a negative binomial distribution which makes the cell-wise recruit process patchy. The smallest size class used is consistent with juvenile growth rates that show that newly settled clams can reach 20 mm by the end of the settlement year (Chintala and Grassle, 1995; Ma et al., 2006).

To simulate a long-term decline in stock biomass as a result of a multi-year period of low recruitment, interannual variability in recruitment was imposed by obtaining a random factor that reduced recruitment more often than it enhanced recruitment, but with a hundred-year average similar to that anticipated from the Beverton-Holt process. Thus, recruitment was imposed with sporadic recruitment pulses that generated relatively large year classes. Although low abundance might trigger depensation in recruitment due to reduced fertilization efficiency (Levitan, 1991; Peterson, 2002; Gaylord, 2008), this process has not been included in the model as the relationship of nearest neighbors to regional density (e.g., Hancock, 1973; Ghertsos et al., 2001) in surfclams is unclear. Furthermore, although hydraulic dredges obviously influence the benthic community (Gilkinson et al., 2005; Morello et al., 2006), the mortality of juvenile surfclams that might be resuspended but not caught by the dredge is unknown although dredge mortality of all size classes is considered to be low (Meyer et al., 1981). No juvenile mortality as a result of fishing is included in the model.

2.8. Choosing a fishing location

A captain chooses a fishing location in the following way. For those captains not searching, the captain calculates the time to steam from the port to each 10-min square in turn. Then the captain calculates how many hours would be required to fill his boat based on his expected LPUE from memory and, in some cases, additional sources of information from other captains or survey data. The captain chooses to fish in the 10-min square yielding the shortest fill time and the least distance from port in order to minimize time at sea while returning to the dock with a full load. This is consistent with standard industry procedure in which plant demand is imposed by regulating the number of fishing trips, not the catch per trip. Interviews with industry representatives emphasize the time-at-sea criterion. The captain is assumed to know LPUE in whole cage units per hour. Thus, a number of 10-min squares may have the same LPUE. Accordingly, the captain identifies one or more 10-min squares that maximize LPUE and chooses among these for his next trip the 10-min square nearest to port. A 10-min square is about 80 nm^2, so that multiple vessels may fish simultaneously in one 10-min square without interference.

2.9. Fishing details

The number of clams harvested during an hour of fishing is calculated from the area swept by the dredge, which depends on the tow speed and dredge width, the efficiency of the dredge, and the size selectivity of the dredge. In addition, the harvest is reduced if the harvest rate per hour exceeds the boat's handling capacity. The number of hours fished is determined by the time necessary to fill the vessel, as constrained by the allowed time on site given the steaming time to return to port. Vessel characteristics were obtained from vessel captains and industry representatives. Selectivity and efficiency relationships were obtained from the federal survey program (e.g., NEFSC, 2013; see also Rago et al., 2006; Hennen et al., 2012).

At the beginning of any fishing hour, if the total catch has reached the boat capacity or if the available time-at-sea has elapsed, fishing stops and the boat returns to port (Table 1). Boat capacity is defined in terms of cages, a volumetric measure, whereas individual clams of varying sizes are caught by the dredge. Numbers are converted to volume based on the number of clams of various size classes per bushel obtained from direct counts of clams of known size. Thus, each sized clam is associated with a volume occupied in the bushel, including clam plus empty space, and the volumes are summed to estimate the total cage volume provided by the dredge haul.

2.10. Survey details and the annual quota

The total fishable biomass (*Fbio*) present on November 1 is used to set the annual quota based on two reference points, biomass at maximum sustainable yield (B_{msy}) and the fishing mortality rate, F_{msy}, yielding *msy* at B_{msy}. F_{msy} was set to 0.15 yr^{-1} (NEFSC, 2013). B_{msy} was set to half of the carrying capacity established by the biomass of the virgin stock after 100 years without fishing. The ACT biomass (*ACTbio* = allowable catch target), which is the allowed annual fishing quota for the next year, is calculated using the

Table 1
Flow diagram for time stepping through the various activities carried out by a fishing vessel. Boat status is checked every hour.

if Current State = WAIT

  if *HomeWait* > 0: Keep waiting and decrement *HomeWait* by 1 hr.

  if *HomeWait* = 0: The next action depends on the weather.

    if Weather ≥ boat type: The weather is too bad. Wait in port for 4 days. Set *HomeWait* to 96 hr (4 days).

    if Weather < boat type: Then fishing is possible. Update the weekly quota if it is a new week. If the remaining weekly quota is at least 90% of the boat capacity, then choose a fish location and go fishing. Set the activity to TRAVEL. Calculate the *TripTime* and *FishTime* for this fishing trip.

if Current state = TRAVEL

  if boat is at the destination:

    if *FishTime* > 0: The boat is at the fishing ground. Set activity to FISH.

    if *FishTime* = 0: The boat is at the processing plant. Set activity to WAIT and set HomeWait to 12 hr. Sell the harvest to the plant and calculate cost and revenue. Update the captain's history for the 10-minute square just fished. Share current catch information with appropriate captains (if active). If boat is not at destination: Continue to travel. Decrement *TripTime* by 1 hr.

if Current State = FISH

  if *FishTime* = 0: Fishing is over. Set activity to TRAVEL; the destination is the plant. Calculate the travel time and set *TripTime*.

  if *FishTime* > 0: Decrement *FishTime* by 1 hr and continue fishing.

following rules that include a 25% reduction in quota due to uncertainty:

$$\text{if } Fbio > 0.5\, B_{msy} \quad \text{then} \quad ACTbio = 0.75\, Fbio \left(1 - e^{-F_{msy}}\right); \tag{1}$$

$$\text{if } Fbio < 0.25\, B_{msy} \quad \text{then} \quad ACTbio = 0; \tag{2}$$

$$\text{otherwise} \quad ACTbio = 0.75\, Fbio \left(1 - e^{\left(-F_{msy} \frac{Fbio}{0.5Bmsy}\right)}\right). \tag{3}$$

The annual quota in biomass is converted to bushels of clams and is capped at 3.5 million bushels. This cap is imposed by the fishery management plan (FMP) (MAFMC, 1986).

3. Simulations

Simulations were designed to permit extraction of information prior to and after a pulsed recruitment event. To accomplish this, a 100-year simulation was conducted following the 100-year spin-up earlier described. The first 25 years were used to permit the simulated fishery to fish down the stock from its virgin state to a stock abundance consistent with observations in the MAB and to allow the captains to lose their initial omniscience. The following 75 years contained a series of pulsed recruitments interspersed by varying periods of low recruitment. We chose two sequences among many that had the following attributes: (a) the time series prior to the pulsed recruitment event was minimally decadal in length without significant recruitment, (b) the time series after the pulsed recruitment event was approximately decadal without significant recruitment, (c) the excursion in fishing mortality rate during the decade prior to the event involved at least a 100\% increase, and (d) the time series of biomass showed a substantial decline but did not trigger the FMP rule resulting in a quota reduction beneath the FMP cap.

Simulations using these recruitment time series were designed to compare a series of behavioral choices available to the captains, identified through interviews with industry representatives and captains. These choices include (a) the degree to which captains rely on recent catch history to determine where to fish, (b) whether a captain undertakes searching behavior to determine where to fish, (c) the degree to which captains communicate with each other about their trips, and (d) the degree to which captains avail themselves of federal survey data (Table 2). Although illegal harvesting is often a component of behavioral choice (e.g., McCay, 1984; Haring and Maguire, 2008; Bashore et al., 2012), the requirement that each cage receive a tag prior to off-loading has eliminated illegal fishing from the surfclam fishery; thus illegal harvesting was not included in this study.

We compared two vessel sizes, small and large, and three ports that encompass the primary homeports in the MAB as they have existed over the recent history of the fishery. Analysis of simulation results focused on the following metrics: the time spent fishing, the differential in catch between that anticipated if all trips returned to port fully loaded and the landed catch, the distance traveled by the boat to the fishing ground, LPUE (calculated as $\frac{landings}{total\ on\text{-}bottom\ time}$), the number of 10-min squares fished per year, and the net revenue for the vessel. Net revenue is calculated relative to a stipulated ex-vessel value of the catch and the cost of fuel; accordingly, relative variations in net revenue are more important than the actual value.

4. Statistics

Time series of vessel performance was standardized to a mean of 0 and a standard deviation of 1. Principal components analysis (PCA) was used to identify the relationship between a suite of time series of this kind. Only factors with eigenvalues $\geq$1 were retained. Time series were of the form of skewed parabolas or hyperbolas. Each time series was analyzed and a suite of diagnostic metrics obtained: skewness, kurtosis, the maximum value, the minimum value, the range of values (amplitude), the first and last years representing the 50th and 25th or 75th (depending on parabola or hyperbola) portion of the amplitude, and the elapsed time in years between each of the pairs of first and last years. These variables were inputted to another PCA and all factors with eigenvalues $\geq$1 retained. Selected metrics were analyzed by ANOVA with main effects being vessel size, captain behavior, and vessel homeport. A Tukey's Studentized Range test was used to identify differences between main-effect categories.

5. Results

5.1. Attributes of scenarios

Certain outcomes of the model depend on the choice of random numbers, particularly the distribution of recruits among 10-min squares. A series of simulations was conducted by Powell et al. (2015) to evaluate the influence of random number on simulation outcome. This analysis showed that the choice of seed number for the random number generator did not substantively affect the economics of the vessel, LPUE, hours spent fishing, average distance traveled from the port to the fishing ground, or the degree to which the vessel returned to port fully loaded. Thus, results presented subsequently are limited to single simulations for each combination of case history, vessel size (small versus large), and captain's behavioral choice.

Table 2
Designations and definitions of captain's traits.

Captain type	Responsiveness	Boldness	Inquisitiveness	Loquaciousness
Responsive	Responsive Memory = 0.2,0.8	Timid Never searches	Indifferent Never uses survey	Taciturn Communication probability = 0
Obdurate	Obdurate Memory = 0.98, 0.99	Timid Never searches	Indifferent Never uses survey	Taciturn Communication probability = 0
Bold	Responsive Memory = 0.2,0.8	Bold Searches on 40% of trip	Indifferent Never uses survey	Taciturn Communication probability = 0
Confident	Responsive Memory = 0.2,0.8	Confident Searches on 20% of trips	Indifferent Never uses survey	Taciturn Communication probability = 0
Inquisitive	Responsive Memory = 0.2,0.8	Timid Never searches	Inquisitive Uses survey	Taciturn Communication probability = 0
Loquacious	Responsive Memory = 0.2,0.8	Timid Never searches	Indifferent Never uses survey	Loquacious Communication probability = 0.5

We examined two case histories (Fig. 3). Both showed similar trends, although differing in some details. The relationship of fishable biomass to fishing mortality rate during an extended series of low-recruitment years followed by a significant recruitment event is shown for both case histories in Fig. 4. Biomass drops early in the time series by a factor of about 5 in one case and 3 in another. Fishing mortality rate rises by a similar factor in both cases. Neither excursion triggers an overfishing definition nor does the quota drop below the FMP cap. Thus, the quota remains constant at the FMP cap. These attributes are consistent with the regulatory environment under which the surfclam fishery has existed in the first decade of the 21st century.

5.2. LPUE

During the simulated low-recruitment event, LPUE declines steadily in both case histories and for both vessel sizes (Figs. 5–6). Recovery occurs more rapidly than the decline in all cases and is delayed by a few years following the recruitment event while new recruits grow to market size. In both cases, LPUE drops from 2 to 4 cages hr^{-1} for the smaller vessels to about 1 cage hr^{-1}. Large vessels drop from 4 to 8 cages hr^{-1} to about 1–2 cages hr^{-1}.

The first two eigenvalues of the PCA using the descriptors of these curves accounted for 69% of the variance in both cases. The first two factor axes were explained by the range in LPUE during the decline in biomass and its recovery (Factor 1) and by the span of years encompassed by the period of low LPUE (Factor 2). A PCA on the time series data showed that eigenvalue 1 accounted for 99% of the variance in Case 1 and 66% of the variance in Case 2. The increased variability in the time series in Case 2 is obvious from a comparison of Figs. 5 and 6. Similarity between time series is primarily a function of the similar trajectories a few years before and after the nadir in LPUE; that is, to a substantive degree, all captains and both boat types respond similarly to the low recruitment event. Dissimilarity is imposed by the prior and subsequent histories bounding the event.

Port location little influenced simulated fishery performance as it responded to a period of low recruitment (Fig. 7). The decline in LPUE during the low recruitment interval was much larger for large vessels, in part due to the fact that these vessels had greater catching capacity in the first place (Fig. 7); however, the decline was also proportionately larger for large vessels, as small and large vessels had low and relatively similar LPUEs when stock abundance declined to low levels. Captain's performance varied the degree to which LPUE declined; however, the two time series differed substantively in the response depending on the behavioral strategy applied to fishing (Fig. 7). Nearly all of this differential originated from the degree of performance at high stock abundance. Thus, the apparent lesser impact on the bold captain is primarily due to the relatively poorer performance of that captain at high abundance. Notwithstanding this trend, the tendency for certain captains to perform poorly under normal stock densities was retained at low stock abundance. Thus nadiral LPUE was lowest for the obdurate captain and the highest nadiral value was obtained for the confident captain in both time series (Fig. 7). The rank order of the captains' performances was similar at high abundance prior to the low-recruitment event and at the nadir of stock abundance when LPUE was lowest.

The duration of low performance as measured by LPUE is a function both of the response to declining stock abundance and the rapidity with which captains locate good fishing grounds when

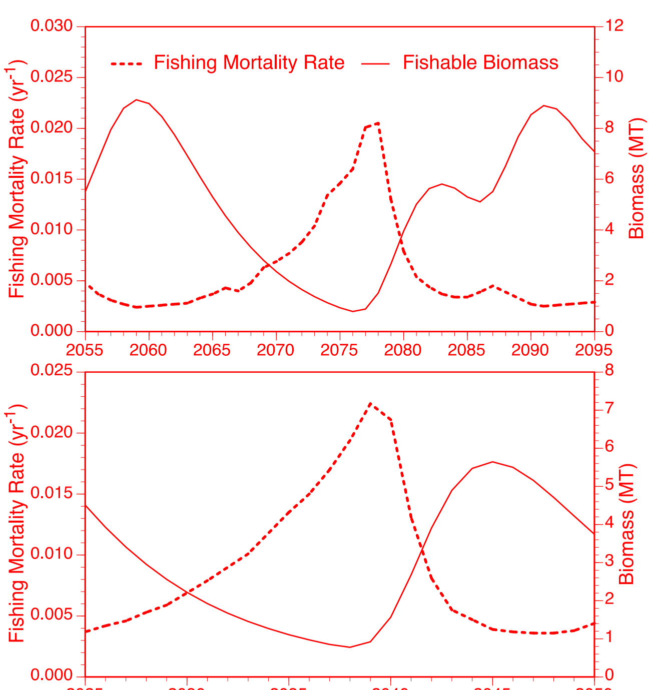

Fig. 4. The time series of fishable biomass (surfclams ≥120 mm) and fishing mortality rate for the two case histories for the time period shaded in Fig. 3. Upper plot is Case 2. Years on the X-axis refer to the portion of the time series used for analysis (Fig. 3).

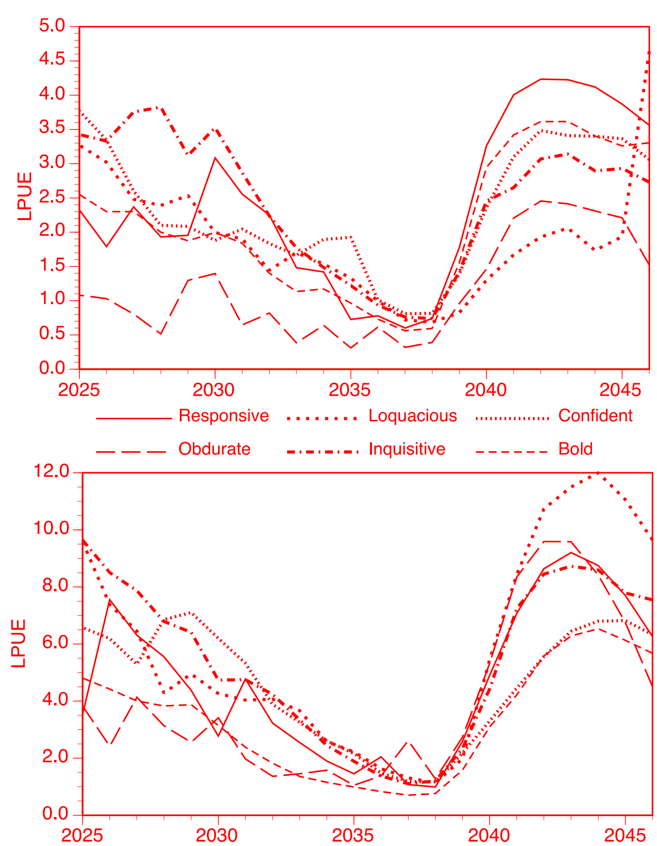

Fig. 5. Landings per unit effort (LPUE in cages hr^{-1}) for Case 1: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

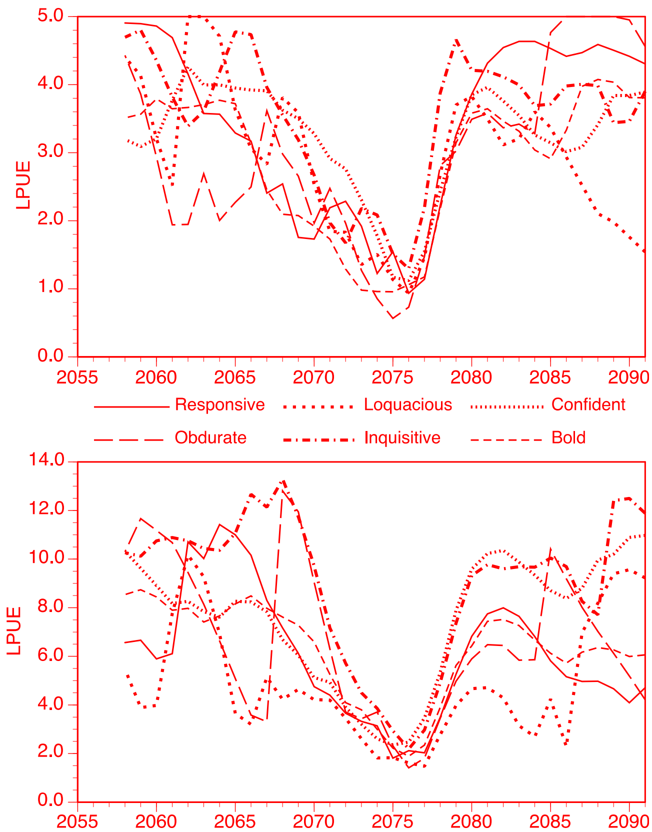

Fig. 6. Landings per unit effort (LPUE in cages hr^{-1}) for Case 2: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

abundance returned. Captains that searched and that used survey data minimized the duration of poor performance (Fig. 7). Port and vessel size did not materially impact the outcome, despite the fact that the southernmost port was characterized by vessels performing more poorly at low stock abundance than vessels fishing out of the two northern ports (Fig. 7). The limited duration of poor performance by captains using survey data attests to the importance of these data in the decision-making process. The fact that the LPUE achieved by these simulated captains rose relatively higher after the return of stock abundance to more normal levels offers further testimony. Moderate searching was also beneficial in one of the two cases in improving performance after stock rebound, but searching in general aided a rapid return to more normal fishing performance. Thus, searching and reliance on survey data minimized the time span of poor performance under simulated conditions of low recruitment and low abundance.

5.3. Hours fishing and catch

During the low-recruitment event, the number of hours spent fishing increased in both simulated case histories and for both vessel sizes as anticipated from the decline in LPUE (Figs. 8–9). The decline in hours fished as abundance recovers occurs more rapidly than the increase does as abundance declines in all cases and is delayed by a few years following the recruitment event while new recruits grow to market size. The first two eigenvalues of the PCA using the descriptors of these curves accounted for 70% of the variance in both cases. The first two factor axes were explained by the range in time spent fishing between the mean values prior to and after the recruitment event and the nadiral value (Factor 1) and by the span of years encompassed by the period of extended fishing time (Factor 2). A PCA on the time series data showed that eigenvalue 1 accounted for 89% of the variance in Case 1 and 85% of the variance in Case 2. The similarity is primarily a function of the similar trajectories a few years before and after the zenith in time spent fishing. Dissimilarity is imposed by the prior and subsequent histories bounding the event.

Generally, vessels fishing from the southernmost port performed more poorly than the remaining vessels in that they spent more time fishing before and after the low recruitment event (Fig. 10). However, vessels from all ports responded similarly as fishery performance responded to a period of low recruitment, with the exception that the period of poor performance tended to extend for a longer time for vessels fishing from the southernmost port. Large vessels spent more time at sea than small vessels. This differential carried through the low recruitment event (Fig. 10); however, the duration of poor performance was similar between the two vessel sizes. Generally captains that often searched (bold captains) and those that used a longer period of remembered fishing performance to identify a fishing location (obdurate) spent more time at sea fishing. Captains that used the survey (inquisitive) spent the least, although these captains rarely differed significantly from other captains except for the former two (bold, obdurate). Captain's performance varied the length of time over which time-spent-fishing was elevated, with obdurate captains performing distinctly most poorly (Fig. 10). In addition, the differential between the time spent fishing at normal abundance levels and the time spent fishing at low abundance was greatest for obdurate captains; at low abundance, these captains spent an unusually long time at sea fishing.

Normally, simulations showed that most vessels returned to port fully or nearly fully loaded. Obdurate captains and captains that often searched (bold) tended to perform less well in Case 1 but the differential was less clear in Case 2 (Figs. 11 and 12). In both cases the recovery was much more rapid than the decline. That is, captains discovered good fishing grounds relatively rapidly once the new pulse of recruits had grown to market size, so that most of the differential in response came from the abilities of the various captains to minimize poor performance during the gradual decline in stock abundance while recruitment remained low. (Figs. 11 and 12).

5.4. Regional coverage

Simulations showed that captains returned frequently to 10-min squares where fishing was good, so that the total number of squares visited per year was 10 or fewer. The exceptions were captains that often or occasionally searched (bold, confident). As abundance declined during the period of low recruitment, the number of 10-min squares visited increased (Figs. 13 and 14), typically rising by a factor of 3–5 at the nadir in abundance. The number of 10-min squares visited yearly is a good indicator of the difficulty that captains encounter in finding good fishing grounds, with the exception of those captains that chronically search.

5.5. Vessel economics

Small vessels routinely lost money during good fishing times, whereas large vessels did not. Most of this differential originated from an assumed older age and therefore higher maintenance requirement for the smaller vessels and the utilization in these simulations of a relatively high price for fuel consistent with the

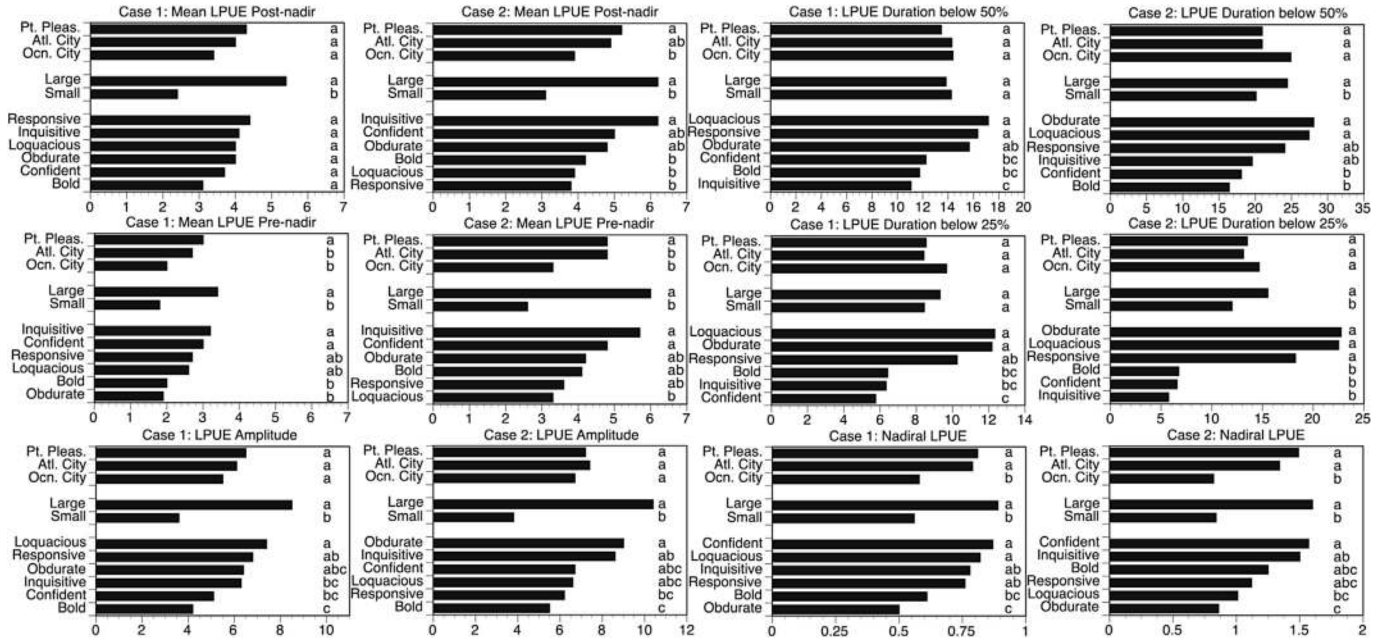

Fig. 7. Average values for LPUE-related metrics and the results of Tukey's Studentized Range tests. Results for each metric are grouped by captain type, vessel size, and port. Different letters within metric and group indicate a significant difference at $\alpha = 0.05$. X-axis values are in terms of cages hr^{-1}, except durations are expressed in years. The metrics analyzed are (a) the mean LPUEs prior to and after the low recruitment event, (b) the amplitude of the change in LPUE during the low recruitment event, (c) the duration of depressed LPUE at the point where LPUE was half of the average pre-event value, (d) the duration of depressed LPUE at the point where LPUE was 25% of the average pre-event value, and (e) the nadiral LPUE. Captain attributes are summarized in Table 2.

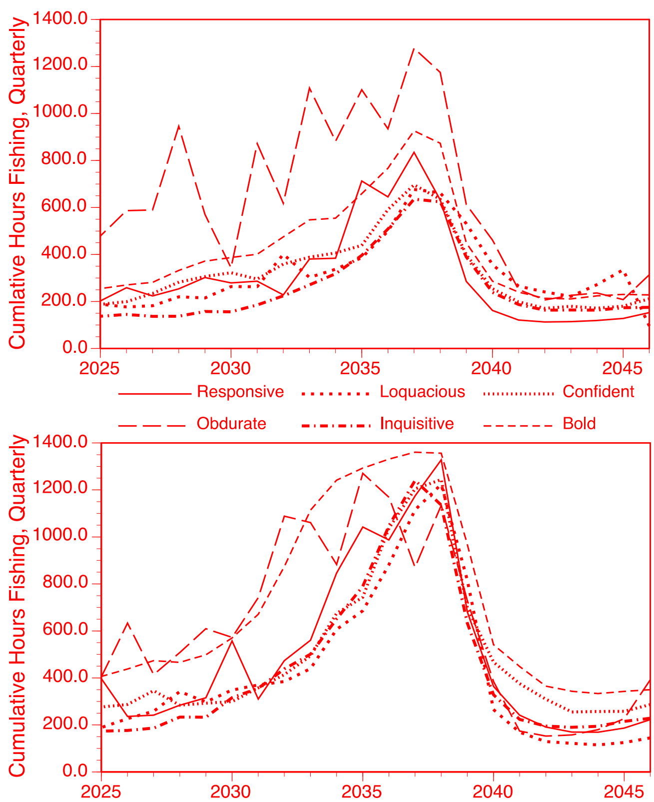

Fig. 8. Average hours fished by a vessel per quarter in Case 1: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

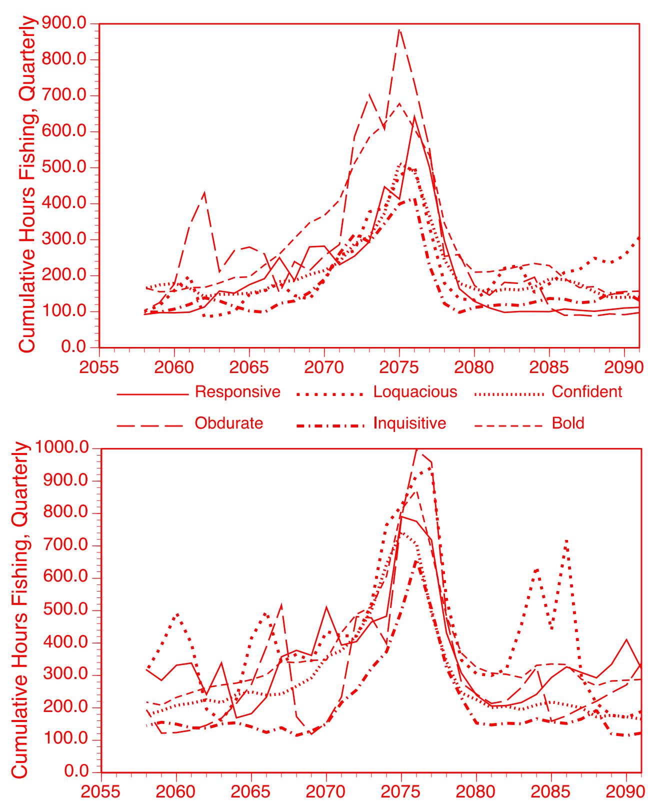

Fig. 9. Average hours fished by a vessel per quarter in Case 2: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time.

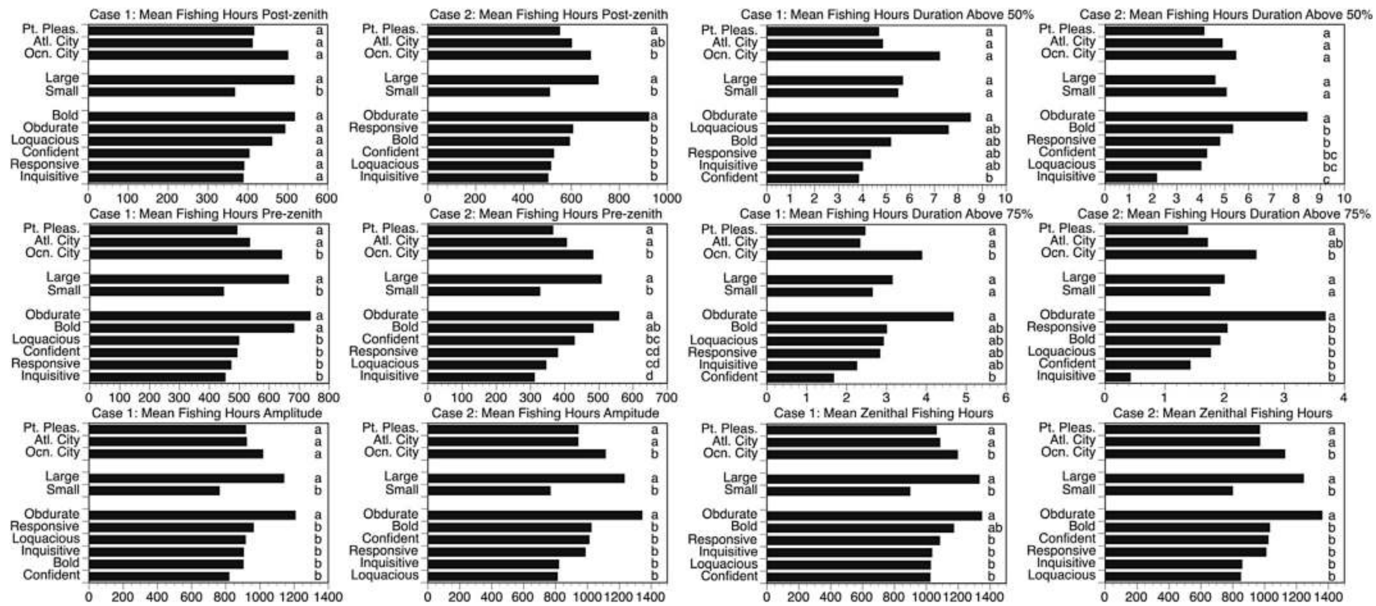

Fig. 10. Average values for metrics describing the per-quarter hours spent fishing and the results of Tukey's Studentized Range tests. Results for each metric are grouped by captain type, vessel size, and port. Different letters within metric and group indicate a significant difference at $\alpha = 0.05$. X-axis values are in terms of hours spent fishing per quarter, except durations are expressed in years. The metrics analyzed are (a) the mean quarterly hours spent fishing prior to and after the low recruitment event, (b) the amplitude of the change in hours spent fishing during the low recruitment event, (c) the duration of increased hours spent fishing at the point where the increase in hours spent fishing was half of the zenithal value, (d) the duration of increased hours spent fishing at the point where the increase in hours spent fishing was 75% of the zenithal value, and (e) the zenith in the hours spent fishing during the low-recruitment event. Captain attributes are summarized in Table 2.

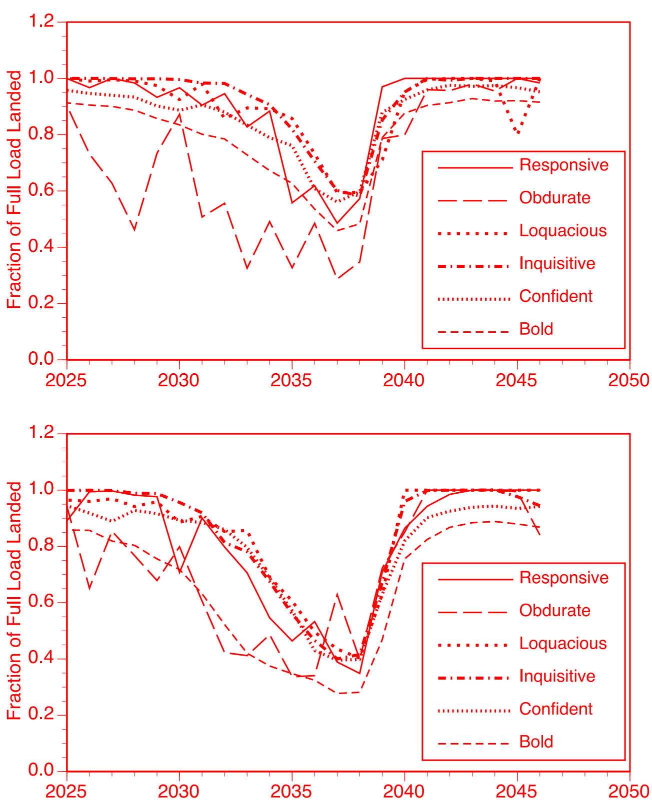

Fig. 11. The fraction of a full load landed by a vessel in Case 1: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

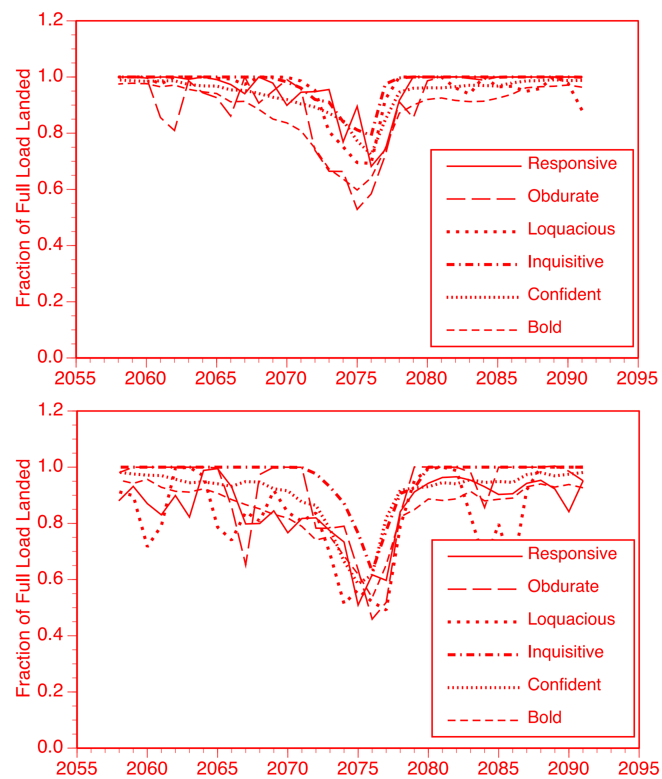

Fig. 12. The fraction of a full load landed by a vessel in Case 2: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

circa-2012 time frame. Net revenue is highly dependent on such assumptions, and vertical integration in the industry limits the importance of specific outcomes, so that economic impact is best determined by the differential between cases for vessels of the same size class. Ergo, analysis of vessel economics focuses on differentials between ports, vessel sizes, and captains' behavioral proclivities.

In all simulations, net revenue declined as LPUE declined (Figs. 15 and 16). Recovery occurred more rapidly than the decline and was delayed by a few years following the recruitment event while new recruits grew to market size. The first two eigenvalues of the PCA using the descriptors of these curves accounted for 70% and 76% of the variance in Cases 1 and 2, respectively. The first two factor axes were explained by the mean, maximum, and minimum value of net revenue across the time series (Factor 1) and by the skewness and kurtosis of the curves and the duration of poor performance as abundance declined (Factor 2). A PCA on the time series data showed that eigenvalue 1 accounted for 91% of the variance in Case 1 and 82% of the variance in Case 2. The similarity is primarily a function of the similar trajectories a few years before and after the nadir in performance. Dissimilarity is imposed by the prior and subsequent histories bounding the event, with most of the variability imposed by the differential in performance of bold captains that tended to see reduced revenues earlier than the remainder and to see the nadiral value drop distinctly greater than the rest.

Generally, net revenue was distinctly lower for vessels fishing

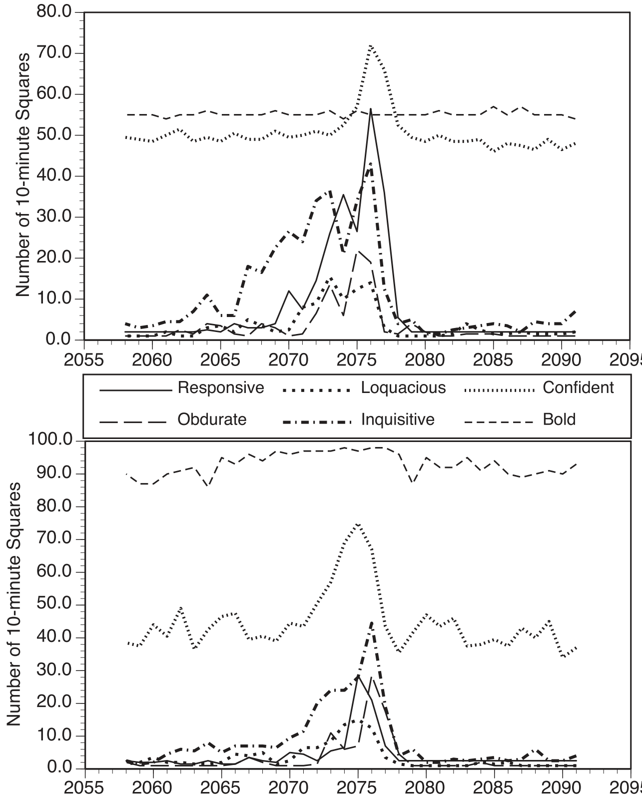

Fig. 14. The average number of 10-min squares fished by a vessel in Case 2: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

from the southernmost port than for vessels fishing from the other two ports (Fig. 17). The decline in net revenue tended to be larger for vessels fishing out of the southernmost port and the duration longer in Case 1, but the latter did not characterize Case 2. The differential between vessel sizes that was inherently present when fishing performance was good little influenced performance during the low recruitment event. Generally simulated performance for both vessel sizes remained poor for a similar period of time. The lower nadiral value for small boats mirrored the differential during periods of good performance; that is, the amplitude of the decline differed little and was not significantly different in Case 1 (Fig. 17). During good fishing times, inquisitive and confident captains tended to perform best; bold and obdurate captains worst. When abundance declined, the drop in net revenue was largest for obdurate and bold captains and least for confident, inquisitive, and loquacious captains. Obdurate and loquacious captains tended to experience poor performance for a longer period of time: confident and inquisitive captains tended to experience poor performance for a briefer period of time. Net revenue dropped to the lowest levels for bold and obdurate captains: inquisitive, confident, and loquacious captains experienced a less negative nadiral value.

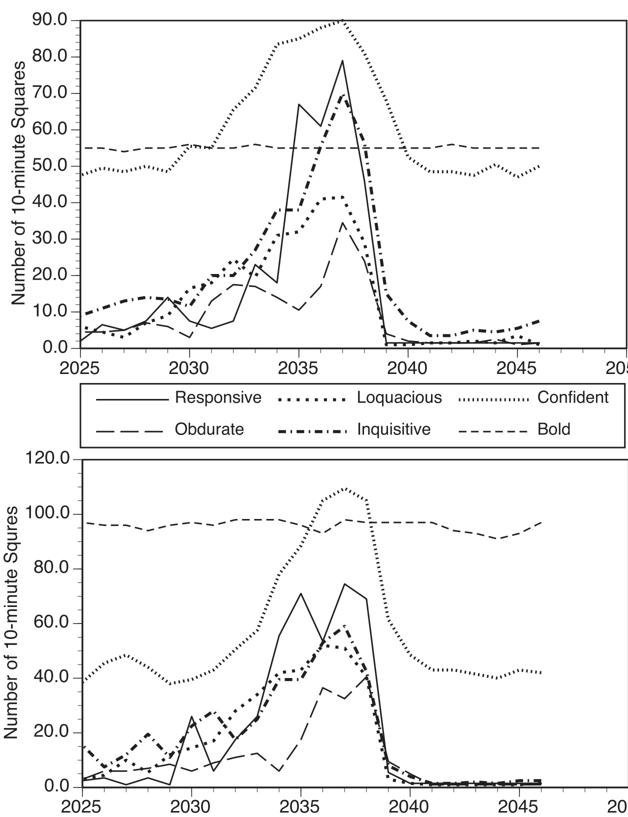

Fig. 13. The average number of 10-min squares fished by a vessel in Case 1: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

5.6. Integrated comparisons

Summary metrics calculated across the span of years in which the metric value fell below half and below the 25% or above the 75% quartile, depending on the direction of change of the metric, of the pre-low-recruitment value reflect both the duration of poor

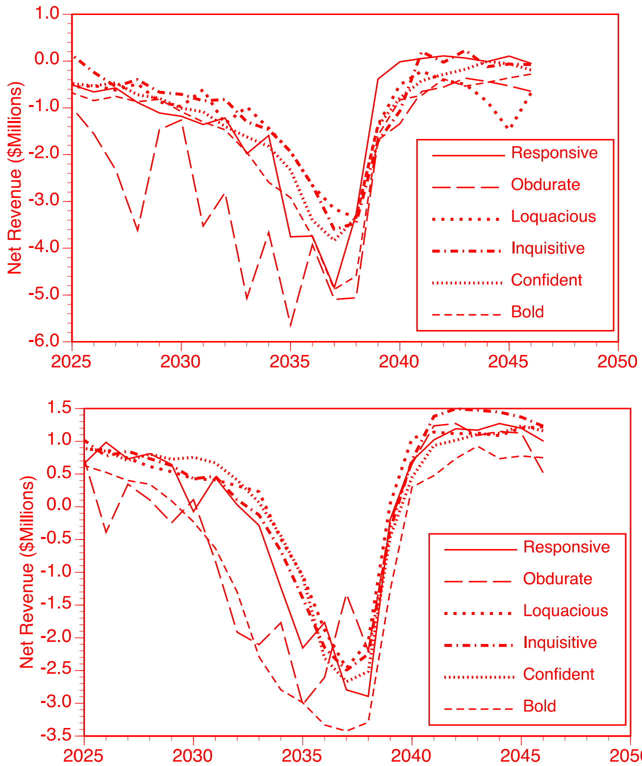

Fig. 15. The yearly net revenue (in millions of dollars) for a vessel in Case 1: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

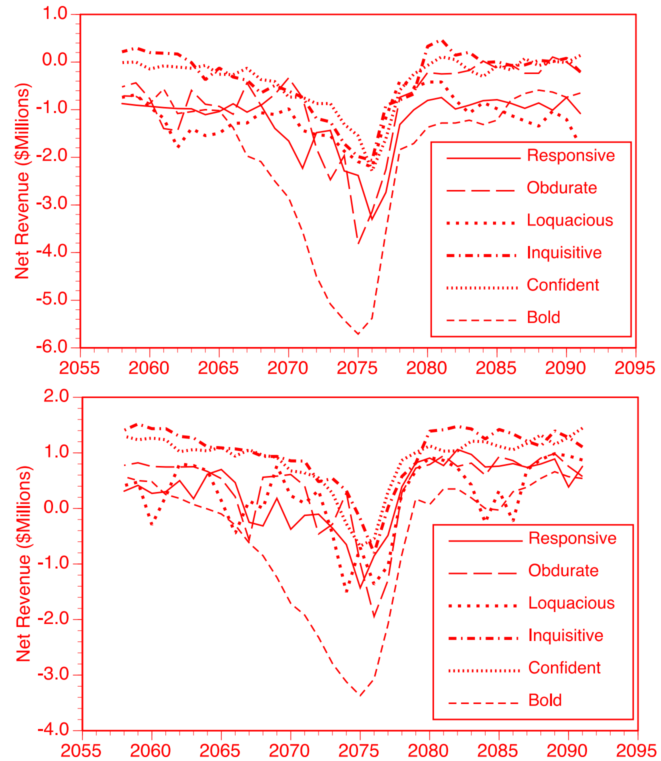

Fig. 16. The yearly net revenue (in millions of dollars) for a vessel in Case 2: upper plot, time series for the smaller vessel; lower plot, time series for the larger vessel. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

performance and the degree of poor performance during those years. We used the geometric mean of the yearly LPUE values and the sum of the hours fished and net revenue for comparison. The geometric mean of LPUE was lowest for the bold and obdurate captains in both cases (Fig. 18). In Case 1, the remaining captains performed similarly over the low-recruitment event. In Case 2, the inquisitive and confident captains performed distinctly better than the rest. This was true over the period of performance below half of the pre-low-recruitment period and generally true for the nadiral period when performance dropped by 75%.

Simulations indicated that the bold and obdurate captains could be expected to spend more time fishing than the other captains during the nadiral phase of the low-recruitment event (Fig. 18). The remaining captains could be expected to perform similarly in relation to the poorer performance of the bold and obdurate captains. Thus, differences in LPUE between the bold and obdurate captains and the remaining captains were a function of longer times fishing due to substandard choices of fishing grounds. Three of the four more successful captains acquired information through survey, search, or communication. However, the responsive captain also performed well, despite the absence of input beyond his own memory.

On the other hand, the bold and obdurate captains limited the impact of low recruitment on earnings to a lesser extent than the other captains. In the case of earnings, the inquisitive and confident captains performed distinctly better than the responsive and loquacious captains in most cases: the differential was most pronounced in Case 2. These two captains had the most up to date information and limited cost under the same LPUE by limiting time at sea, not just time fishing. On average, these captains fished nearer to the home port and returned more predictably with a full load, thus improving net earnings under similar LPUEs.

6. Discussion

6.1. Perspective

We simulated an extended period of low recruitment during which market-size abundance declined by about a factor of 5 over a period of about 10 years. The decline occurred gradually, but was followed by a recruitment event that rapidly returned biomass to the original higher levels. The fishing mortality rate rose from low levels to 0.02–0.025 yr^{-1}, values that are consistent with a period of low recruitment observed during the present-day fishery (NEFSC, 2013). During this excursion in biomass, LPUE declined as lower abundance required an extended time at sea to catch a full load. Vessels more frequently returned to port without a full load. Captains expanded their geographic range of interest, occupying increasingly more 10-min squares in an effort to maintain their performance. Net revenue declined as increased time at sea and increased fuel consumption, abetted by lower catch, reduced vessel revenues and increased vessel costs. None of these changes is unanticipated.

We examined two case histories that differed in a host of particulars, but the overall trends were the same, as were the responses by the fishing vessels; the performance curves followed

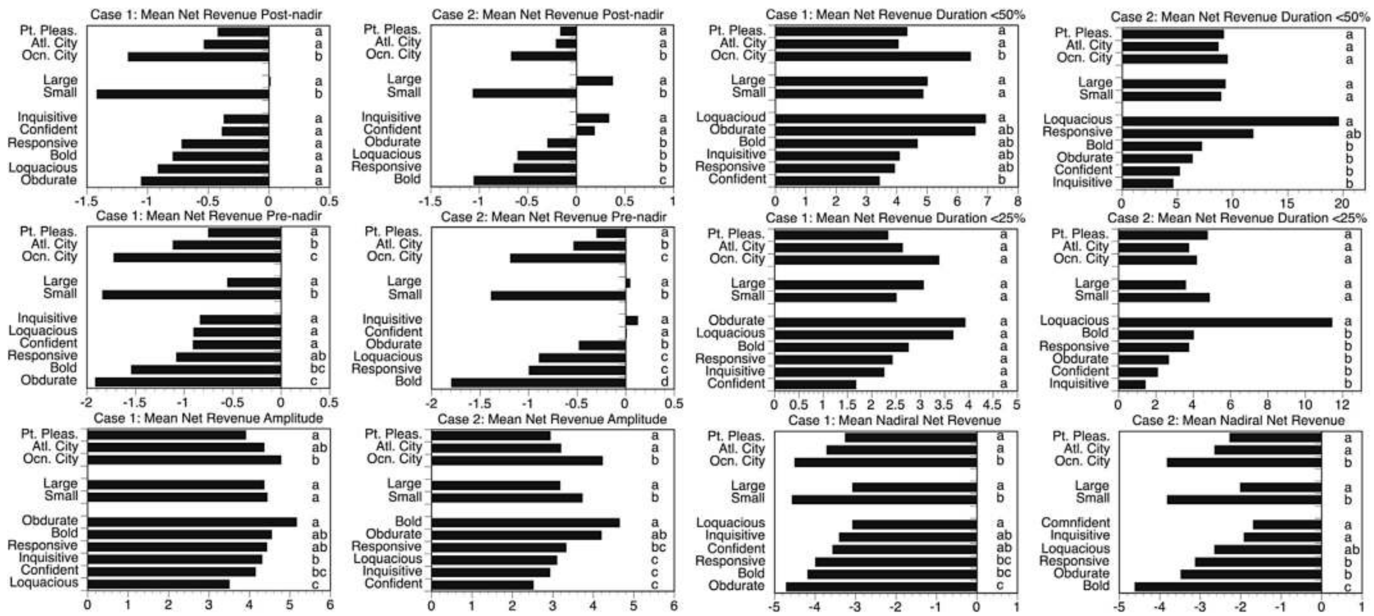

Fig. 17. Average values for metrics describing the yearly net revenue (in millions of dollars) and the results of Tukey's Studentized Range tests. Results for each metric are grouped by captain type, vessel size, and port. Different letters within metric and group indicate a significant difference at $\alpha = 0.05$. X-axis values are in term of millions of dollars, except durations are in years. The metrics analyzed are (a) the mean net revenue prior to and after the low recruitment event, (b) the amplitude of the change in net revenue during the low recruitment event, (c) the duration of diminished net revenue at the point where the decline in net revenue reached half of the initial mean value, (d) the duration of diminished net revenue at the point where the decline in net revenue reached 25% of the initial mean value, and (e) the nadiral value of net revenue during the low-recruitment event. Captain attributes are summarized in Table 2.

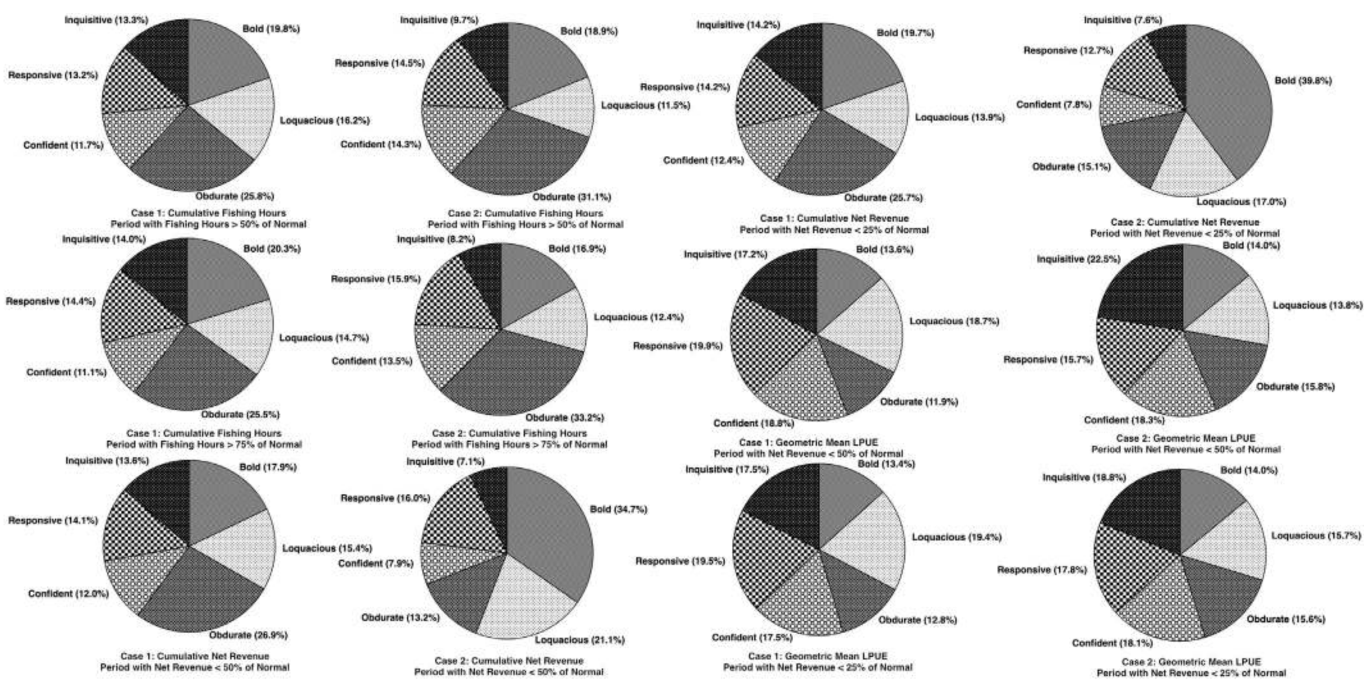

Fig. 18. Summary metrics for each of the two cases for LPUE, hours spent fishing, and net revenue expressed as the percent contribution to the sum of six values, one for each captain type. The metrics analyzed are (a) the mean value prior to and after the low recruitment event, (b) the amplitude of the change in value during the low recruitment event, (c) the duration of increased or diminished values depending on metric, for the metric at the point where the change reached half of the initial mean value, (d) the duration of increased or diminished values depending on metric, for the metric at the point where the change reached 75% or 25% respectively of the initial mean value, and (e) the zenithal or nadiral value, depending on metric during the low-recruitment event. For each, six captain types are shown: responsive, the standard captain; obdurate, a captain that uses a longer memory of performance to identify fishing locations; loquacious, a captain that communicates catch performance with other captains; inquisitive, a captain that uses survey data; confident, a captain that searches 20% of the time; bold, a captain that searches 40% of the time. Captain attributes are summarized in Table 2.

the same trajectories as quantified by the high degree of variance explained by Factor 1 in the time-series PCAs. Thus, to a substantial degree, the simulated fisheries performed comparably over two different but analogous case histories and among the various boats, ports, and captains' behavioral proclivities.

6.2. Behavioral choice by captains

The purpose of the study was to examine the anticipated responses of captains of varying behavioral proclivities to the challenge of declining stock abundance. Powell et al. (2015) found little difference in performance amongst captains of differing proclivities during times of limited excursions in stock abundance or distributional pattern. In the case examined here, simulated captains faced extreme challenges as the fishing mortality rate increased by over an order of magnitude and stock declined by a factor of about 5.

We examined a range of typical behaviors observed for captains in the present fleet and reported to have occurred over the course of the history of the fishery. This included captains that utilized stock survey data to identify fishing locations (inquisitive captains), captains that searched occasionally (confident captains) or frequently (bold captains), captains that shared information on their catches (loquacious captains), and captains that tended to integrate a shorter period (responsive captains) or a longer period (obdurate captains) of their catch history into their decision-making process (Table 2).

To a substantial degree, all captains responded similarly to a period of low recruitment. LPUE slowly declined. Captains tended to travel farther from port as 10-min squares nearer their ports were fished down. As a consequence, the tendency for boats to return to port fully loaded decreased. Time spent fishing also increased as 10-min squares initially with lesser clam densities became favored as originally favored 10-min squares were fished down. The number of 10-min squares visited increased as the nadir of abundance was approached. Thus, all captains accessed a much larger portion of the domain in order to reduce the rate of decline in LPUE. In the end, however, no behavior was sufficient to offset the decline in abundance, so that both LPUE and hence net revenue plummeted.

Despite the similarity in responses between captains, important differences exist in the particulars of the response; the rank order of captains' behavior varied between metrics and between the two scenarios. Thus, the drop in LPUE was largest for the loquacious captain in Case 1, but the loquacious captain performed about average by the same metric in Case 2. However, at a somewhat more general level, captains that obtained information from survey data or by searching limited the impact of low recruitment on LPUE. For those captains that used the survey (inquisitive) or moderately searched (confident), the lesser decline in LPUE was reflected in the lesser decline in net revenue and a lesser increase in total fishing hours. This did not occur for the captain that searched frequently; a lesser decline in LPUE did not reflect positively in other metrics. Rather, LPUE was low initially and declined to the lowest nadiral value, although the amplitude was less due to the lower starting point, and time spent fishing remained high which limited the LPUE decline. Thus occasional searching derived benefits, whereas frequent searching did not.

The degree of change in a metric is consequential, but the elapsed time underperforming is at least as important. Here, we examined the time that passed with performance less than 50% and less than 25% or greater than 75%, depending on the metric, of original performance levels. Simulations showed that captains that searched or used survey data limited the duration at which LPUE was low because they were able to limit the duration of time when time spent fishing was unusually high. Moderate searching performed better than frequent searching once again. For this reason, the duration of time when net revenue was low was less for these captains.

The responsive captain, the captain that based choices on the most recent catch history, performed about average according to all metrics, not as well in most cases as captains that searched moderately or used survey data, but better than captains that communicated or employed a longer record of catch history in deciding locations to fish. The latter is not surprising. What is surprising is how poorly captains that communicated performed. These captains suffered a relatively long duration of poor performance; net revenue was low for a longer period of time although the amplitude of decrease was less than for some other behavioral types. LPUE tended to be relatively low for these captains generally, but declined less. Time spent fishing was consistently relatively low, but this did not translate into LPUE performance. LPUE reached a lower nadiral value than most, but part of this response originated in the lower initial value under normal conditions of abundance. Loquacious captains performed much better in Case 1 than in Case 2, so the response was unusually case dependent. In these simulations, loquacious captains gather information haphazardly from other captains. Some of this information is good, e.g., from confident or inquisitive captains, and some of it is less good, e.g., from bold or obdurate captains. Thus, these captains implement a mixture of good and less good choices, as they treat all information with equivalent cache.

6.3. Impetus for behavioral adaptation

Powell et al. (2015) examined a range of captains' behaviors under standard fishing conditions during a period of relatively constant and high stock abundance. Under these conditions, behavioral choice made little difference in the outcome. Powell et al. (2015) examined the influence of climate change by comparing the 1990s period to that of the 2000s. Surfclams are sensitive to bottom water temperatures above about 21 °C (Weinberg, 2005; Munroe et al., 2013). As a consequence, warming of the MAB (Scavia et al., 2002; Jossi and Benway, 2003; Kerr et al., 2009; Narváez et al., 2015) has resulted in a range contraction for this species since the mid-1990s (Weinberg et al., 2002, 2005; Weinberg, 2005). A large-spatial-scale mortality event occurred at the southern boundary of the surfclam's range coincident with this rise in bottom water temperature (Kim and Powell, 2004; Narváez et al., 2015) driving the southern boundary northward and the inshore boundary offshore (Weinberg et al., 2002). This decadal redistribution of the stock has resulted in a redistribution of fishing effort accompanied by the movement of processing plants northward and the shift of vessels from southerly ports northward. The opening of Georges Bank has alleviated the forced regional compression of the fishery to some extent. Despite these fishery responses, the fleet remaining in the MAB now focuses heaviest fishing pressure in a smaller region. Powell et al. (2015) concluded that the range contraction did not favor or debit any captain's behavioral choice disproportionately. Thus, the difference in performance amongst captains of various behaviors is a nuanced one, if fishing conditions are stable and abundance not unduly low.

Contrast these results from steady state conditions to those obtained in the present study. In our study, simulations subjected captains to highly variable population dynamics that stressed performance by reducing the density of market-size surfclams. The behavioral proclivities of captains substantively influenced the outcome. Use of survey data, made available every three years, significantly improved performance. About equal in positive effect was moderate searching. The survey is essentially a comprehensive search, but available only periodically. Moderate searching results in updated information more frequently, but over a smaller area.

Other behaviors incurred penalties. Communication failed to provide improved performance because both poor and good information was transferred. Reliance on a long period of catch history failed to improve performance because too much information was out of date during a time of rapidly changing conditions. Frequent searching underperformed mostly because frequent searching in and of itself represents an additional cost factor and takes time away from fishing; as a consequence, the benefit of frequent searching in providing up-to-date information did not counterweigh the inherent liabilities associated with the activity.

Searching is an important component of captains' decision-making process in many fisheries (Gillis et al., 1993; Dorn, 2001; Powell et al., 2003a). Powell et al. (2015) noted that captains desire to search more than vessel owners will permit. The dichotomy driving this differential is the difference between moderate and frequent searching. In this study, moderate searching improved performance: frequent searching deteriorated performance. What approach to use to optimize searching time is unclear, however. Moreover, frequent searching during a period of declining stock abundance proved to be much more injurious to performance than under conditions of stable population dynamics (e.g., Powell et al., 2015) whereas occasional searching during a period of declining stock abundance proved to be much more advantageous than under conditions of stable population dynamics. Thus, the question of when and how frequently to search becomes more significant as fishery performance declines.

7. Conclusions

For surfclams, recruitment during the 2000s has averaged much below recruitment in the 1985–1995 period in the MAB (NEFSC, 2013). Six of the 7 lowest recruitment years since 1978 occurred in the 2000s, as estimated by the most recent federal stock assessment (NEFSC, 2013). Thus, the 2000s have been an extended period of low recruitment. Fishing mortality rates have risen as abundances declined (NEFSC, 2013). The contraction in range has exacerbated this trend. The simulations we present represent an extended period of low recruitment, but extended periods of low recruitment clearly fall within the ambit of the surfclam's population dynamics. Management of the surfclam fishery has been relatively noncontroversial as the quota cap in the FMP has remained far below the overfishing limit, even under a period of low recruitment. An important contributing factor is the geographic extent over which surfclams live at relatively low abundance. That is, the total population abundance is supported to a considerable extent by vast areas of low surfclam density. Such areas are unfishable, as LPUEs are too low. The surfclam fishery sees stock abundance in terms of patches of high density. Boats fishing in areas of low abundance cannot fill their holds in the allotted time for a trip, typically in the summer 48 h dock to dock. Thus, the impact of low recruitment is realized much more rapidly by the fishery than by the stock.

LPUE has proven to be a difficult metric to evaluate in the stock assessment. Presently, trends in LPUE are not used to evaluate the stock and fishery relative to the sustainable yield reference points, B_{msy} and F_{msy} (NEFSC, 2013), because the fishery tends to concentrate on a few 10-min squares supporting high surfclam density (e.g., Figs. 13 and 14). These squares are slowly fished down creating a stock-wide decline in LPUE that is not normally reflected in a change in abundance for the stock as a whole. The dynamics do not necessarily mean that fishery performance is endangered by low stock abundance as captains tend to revisit 10-min squares for some time before searching for new areas to fish. As a consequence, evaluation of the impact of low recruitment as it imposes a constraint on the availability of patches supporting adequate LPUE is a challenge.

This study identifies some metrics that might be gleaned from landings data that would suggest a restriction in adequate fishing opportunities imposed by a drop in abundance and particularly a drop in the availability of high-density components of the population. We suggest that the number of 10-min squares visited by captains will increase under these conditions. LPUE will drop and the drop will be dominated by the time spent fishing which will increase. The distance traveled will also tend to increase as many of the new 10-min squares that are accessed will be farther from port. Total time at sea will increase and, assuming that refrigeration equipment is not installed, vessels will return to port without a full hold increasingly often. We have not examined management measures that might respond to these constraints. As is true in today's fishery, the restrictions that so influenced vessel behavior nonetheless occurred under stock biomasses that did not trigger restrictions imposed by federally-mandated guidelines. Thus, grave dislocations in the fishery can occur even if federally-mandated guidelines on stock status are fully met. We note, for example, that fishing mortality rate in our simulations exceeded 0.02 yr^{-1} for only a few years. Fishing mortality rates have been about twice this high since 2003 in the northern New Jersey region south of Hudson Canyon that supports the bulk of the fishery (NEFSC, 2013). LPUE has declined. It would be interesting to determine the per-vessel 10-min square visitation rate over this time period and to investigate the reasons for differential responses between vessels and vessel captains.

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