OCS Study
BOEM 2022-065

Understanding Economic Impacts to the Commercial Surfclam Fishing Industry from Offshore Wind Energy Development

US Department of the Interior
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DISCLAIMER

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ABOUT THE COVER

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List of Abbreviations and Acronyms

ABC	Allowable Biological Catch
BOEM	Bureau of Ocean Energy Management
CPUE	Catch Per Unit Effort
DOI	US Department of the Interior
EIA	Energy Information Administration
ESP	Environmental Studies Program
ESPIS	Environmental Studies Program Information System
LPUE	Landings Per Unit Effort
MAFMC	Mid-Atlantic Fisheries Management Council
MAFMC SSC	Mid-Atlantic Fisheries Management Council Scientific and Statistical Committee
MSA	Magnuson-Stevens Fishery Conservation and Management Act
NEFSC	Northeast Fisheries Science Center
NMFS	National Marine Fisheries Service
NRMSE	Normalized Root Mean Squared Error
SEFES	Spatially Explicit Fisheries Economic Simulator
TMS	Ten-Minute Square; bounded by 10 minutes of latitude by 10 minutes of longitude

1 Abstract

The offshore wind energy industry is advancing rapidly and plans for several facilities along the U.S. Atlantic coast are currently under environmental review. The potential effects of wind energy development on marine fisheries resources have gained attention due to the ecological and economic importance of the fisheries and for the repercussions to fishing communities. The Atlantic surfclam fishery (*Spisula solidissima*) is one of the most exposed fisheries to impact from offshore wind energy development due to port location, the overlap of fishing grounds and wind energy areas, and the nature of the gear and vessels used. Once built out with turbines, cables, and scour protection, Atlantic surfclam fishing and survey operations within wind energy areas may be reduced or eliminated due to vessel limits, safety requirements, and assessment protocols. Exclusion of these activities in certain regions will have consequences to the behavior and economics of the fishery and the scientific and management products employed in this fishery which could have downstream ecological or economic effects. Using a modeling tool (*SEFES*) that integrates spatial dynamics in surfclam stock biology, fishery captain and fleet behavior, federal management decisions, and fishery economics, the impact of excluding fishing and survey efforts from wind energy areas were examined. Model simulations allow *in silico* experiments to be conducted that prevent fishing vessels from accessing wind energy lease areas (displacement) or prevent vessel from fishing or transiting through wind energy lease areas. Our simulations include scenarios in which fishing displacement occurs cumulatively across all wind energy projects (Chapter 5), as well as scenarios in which displacement is limited to wind projects in individual regions (Chapter 6). Additionally, our model simulates the semi-annual stock assessment survey that is conducted on commercial vessels and is used in management of the fishery and stock. Simulations included scenarios that allowed evaluation of changes in survey results due to the inability of the survey to access wind energy lease areas (Chapter 7). At the time of model development and initial simulations (Chapter 5-7), the wind energy areas now delineated as the New York Bight lease areas had not been determined. Consequently, our initial simulations included a larger contiguous block that was identified as potential future wind energy areas to be considered for leasing (‘Call Areas’ in Chapters 5 -7). Portions of the ‘Call Areas’ were removed from consideration as BOEM identified the ultimate blocks for the New York Bight lease areas. Finally, our simulations include lease area designations that are specific to the footprint of the New York Bight lease areas, as opposed to the larger NY Bight “Call Areas” that were used in earlier chapters, and designated transit corridors for vessels passing through the New York Bight wind lease areas (Chapter 8).

All simulation strategies were informed via detailed interviews and input from advisory teams from industry, management, and BOEM. Imposing exclusionary restrictions on Atlantic surfclam vessel fishing and transit across wind energy areas increased fishing trip travel time and total time at sea, leading to reductions in the number of trips taken by the fleet and increased costs associated with displaced fishing effort. The simulated cumulative economic revenue losses range from 3% to 15% depending on the scenario simulated; however, for restrictions imposed for region B (off New Jersey) revenue losses up to 26% are seen for the Atlantic City fleet alone. Further, our simulations indicate that exclusion of the stock assessment survey from wind energy areas will make approximately 3% to 17% of the Atlantic surfclam spawning stock biomass inaccessible to the survey. This loss of biomass to the survey will cause perceived fishing mortality to increase by 0.7 to 7.3% because of the combination of reduction of observable stock biomass and changes in catch due to changes in fishing behavior. This evaluation of the possible scale of impacts of offshore wind development on the Atlantic surfclam fishery and its

management can help inform strategies to allow coexistence of multiple sectors of ocean users. Understanding the impacts of fishery exclusion and fishing effort displacement from offshore wind energy development is critical to the sustainability of various fishing industries on the Northeast U.S. continental shelf.

2 Introduction

Increasing industrialization and expanded uses of the coastal ocean are producing challenges for established and new ocean users because of overlapping and competing needs, such as conflicts between existing fisheries, offshore renewable energy, and aquaculture industries (Arbo and Thủy, 2016; Schupp et al., 2019). Offshore development is coincident with a warming climate that is altering the coastal ocean habitat and distribution of commercial fish stocks, posing a threat to the stability and productivity of marine fisheries (Kleisner et al., 2017; Free et al., 2019; Rogers et al., 2019). Tools that can predict and proactively manage these complex and interconnected challenges to marine fisheries are increasingly important for managers and planners to evaluate costs and benefits of strategies that support multiple users of the offshore environment.

Fisheries in the Northeast and Mid-Atlantic regions of the U.S. are culturally and economically significant, generating nearly USD 2 billion in revenues annually and supporting over a hundred thousand jobs (NMFS, 2021). Many of these fisheries occur in areas that are designated for installation of large-scale wind turbine arrays to advance blue-water energy production (Methratta et al., 2020). As of 2021, over 1.7 million acres were leased for offshore renewable energy projects on the outer continental shelf, with most of the leased acreage occurring in the Northeast and Mid-Atlantic (BOEM, 2021), where significant wind power potential exists (Archer and Jacobson, 2005). This anticipated expansion of offshore wind energy production on the Mid-Atlantic Bight (MAB, Figure 1) continental shelf comes with considerable uncertainty in the potential impacts to the physical environment, biological resources, and dependent human communities (Gill et al., 2020; Haggett et al., 2020; Methratta et al., 2020; van Berkel et al., 2020). In particular, the economic effects of this offshore wind energy development on U.S. Northeast and Mid-Atlantic commercial and recreational fishing sectors are as yet unknown, though economic analyses suggest exposure to economic risk varies among fisheries and across ports (Kirkpatrick et al., 2017).

Offshore wind energy development can affect fisheries and fishery resources through several pathways that include habitat alteration, changes to sound and energy landscapes, fisheries exclusion, and fishing effort displacement (Bergström et al., 2014; Gill et al., 2020). Additionally, effects on fish populations and fishing behavior may lead to downstream impacts for fishing businesses, support services, and coastal communities (Hooper et al., 2018). Fishery exclusion occurs when legal restrictions on fishing activities or vessel transit within offshore wind areas exclude fishing operations, or when lack of insurance coverage, added challenges related to navigational safety, or limited coordination and cooperation among wind energy and fishing sectors lead to de facto exclusion (Gill et al., 2020). In the U.S. context there are no legal restrictions on fishing activities or vessel transit in offshore wind facilities. Nonetheless, changes in the spatial distribution of fishing activity, or fishing effort displacement, may occur as a result of direct or indirect exclusion, or because alternative fishing locations become more or less advantageous in response to changes in transit routes, operational considerations, or fishing conditions. Studies that provide quantitative evaluations of commercial fishery exclusion and fishing effort displacement in relation to offshore wind energy development are limited, despite these factors being frequently cited as drivers of use-conflict (Hall and Lazarus, 2015; Hooper et al., 2015; Haggett et al., 2020). Such analyses are integral to understanding the cumulative impacts of offshore wind energy development (Berkenhagen et al., 2010; de Groot et al., 2014; Gill et al., 2020; Haggett et al., 2020).

The Atlantic surfclam (*Spisula solidissima*), a long-lived and large-bodied clam, supports a fishery that is a major economic driver for communities from Virginia to Massachusetts (Figure 1). Collectively, the

Atlantic surfclam and ocean quahog (*Arctica islandica*) fisheries were estimated to generate USD 1.3 billion annually in total economic impacts (Murray, 2016) and the Atlantic surfclam fishery landings alone exceed 30 million USD (ex-vessel) in annual revenue. The distribution of the Atlantic surfclam population is confined to the inner and mid-shelf of the Mid-Atlantic Bight (MAB, Figure 1); areas suitable for offshore wind energy development. Moreover, landings from the Atlantic surfclam fishery to the major ports (Atlantic City, NJ and New Bedford, MA, Figure 1) come from areas slated for development as offshore wind energy (Methratta et al., 2020). The vessels and gear used to harvest Atlantic surfclams (large vessels with hydraulic dredges) make fishing in and around wind energy infrastructure, such as buried cables and support structures, highly uncertain, which exacerbates economic vulnerability of the fishery to wind energy lease areas (Kirkpatrick et al., 2017).

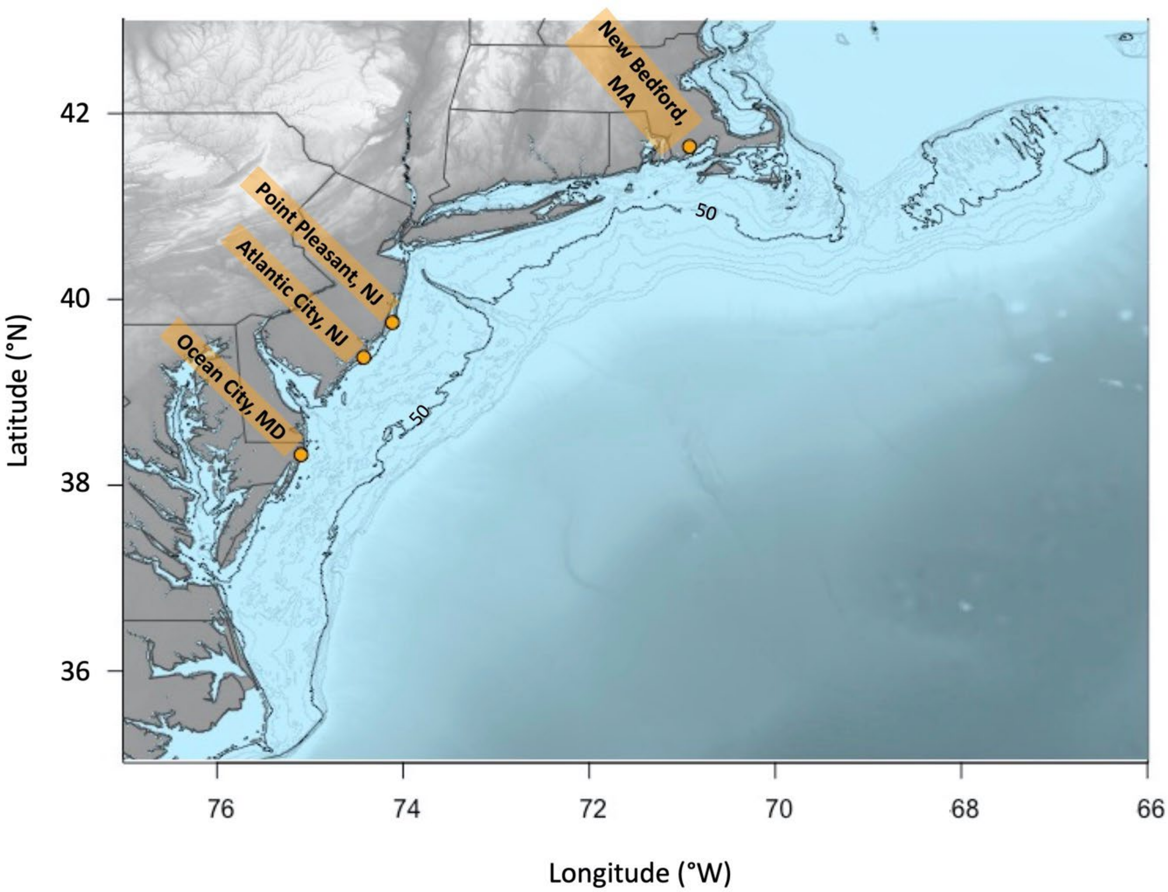


Figure 1. Surfclam habitat and ports.
Map of the Mid-Atlantic Bight showing locations of the major ports for the Atlantic surfclam fishing fleet (orange circles). Over much of the MAB, Atlantic surfclam habitat on the continental shelf is bounded inshore by the 10-m isobath and offshore by the 50-m isobath (black line).

The Atlantic surfclam fishing sector is highly consolidated and vertically integrated, with processing plants owning or controlling nearly all harvest quota and vessels operating in the fleet (Northern Economics, 2019). A large portion of processed product is supplied to a small number of national and multinational food service and soup companies. This market structure, in addition to persistent competition from imports, leaves processors little ability to control prices (Mitchell et al., 2011; Northern Economics, 2019). Small shifts in profitability caused by changes in vessel operations, harvest, and landings could therefore be consequential at the port or industry level. As industrialization of the ocean expands, there is a growing recognition that quantification and mitigation of adverse socioeconomic impacts is necessary to achieve sustainable and inclusive blue economic growth (Bennett et al., 2019; Haggett et al., 2020). Understanding the impacts of fishery exclusion and fishing effort displacement from development of offshore wind energy is critical to the sustainability of the Atlantic surfclam fishing industry.

The interconnectivities of offshore wind energy development, warming temperatures, and Atlantic surfclam population distribution are complex, making evaluation of the fishery's exposure to these stressors difficult. Identifying and assessing potential outcomes and impacts, with associated costs and benefits, is integral to developing mitigation strategies that will afford some level of sustainability for the Atlantic surfclam fishery. Thus, quantitative evaluations of interactions between offshore wind energy development and on the Atlantic surfclam fishery, with particular focus on economic impacts, are needed.

The spatially explicit, ecological-economic agent-based Atlantic surfclam fishery model (*SEFES*) used in this study provides the capability for quantitative evaluations of the fishery and its economics. Components included in *SEFES* represent the fishable stock, fishing behavior, structure of the fishing fleet, and economic conditions of the seafood industry. Detailed description of the model structure is provided in Chapter 3. Inclusion of fisher experiential knowledge in agent-based model development and validation is key to ensuring model realism, and acceptance and use of simulation results. Further, stakeholder participation in agent-based modeling approaches helps ensure their use and value in management decision making. Our *SEFES* model implementations engaged experts from both the fisheries (11 captains and 5 company owners/managers) and the management (5 persons who have worked in federal management agencies for surfclams) sectors early in model conception and development. This co-development approach helped to support realistic dynamics of the simulated biological, economic and social systems relevant to the intended model use. Input from these expert advisors, including active captains in the fisheries, provided the basis for decision making parameterizations included in the model and for assessing the simulated patterns of fishing fleet behavior (Chapter 4).

Model simulations allow *in silico* experiments to be conducted that prevent fishing vessels from fishing in wind energy lease areas (displacement) or prevent vessel from fishing and transiting through wind energy lease areas. Our simulations include scenarios in which fishing displacement occurs cumulatively across all wind projects (Chapter 5), as well as scenarios in which displacement is limited to wind projects in individual regions (Chapter 6). Additionally, our model simulates the semi-annual ~~stock assessment~~ survey that is conducted on commercial vessels and is used in management of the fishery and stock. Simulations included scenarios that allowed for evaluation of changes in survey results due to the inability of the survey to access wind energy lease areas (Chapter 7). At the time of model development and initial simulations (Chapter 5-7), the wind energy areas now delineated as the New York Bight lease areas had not been determined. Consequently, our initial simulations included a larger contiguous block that was identified as potential future wind energy areas to be considered for leasing ('Call Areas' in Chapters 5 -7). Therefore, our simulations also include lease area designations that use specifications for the footprint that is now designated as the New York Bight lease areas and designated transit corridors for vessels passing through the New York Bight wind lease areas (Chapter 8). All simulation strategies were informed via detailed interviews and input from advisory teams from the surfclam fisheries and management sectors, and BOEM. We anticipate these simulations will improve understanding of how new offshore wind energy infrastructure may affect the economics of the Atlantic surfclam commercial fishery.

3 Model Structure

3.1 Model Overview

The model developed and implemented in this project, **S**patially-**E**xplicit **F**ishery **E**conomics **S**imulator (*SEFES*), includes components that simulate Atlantic surfclam fishable stock, processing plant economics, and fishing fleet behavior and economics (Figure 2). The Fishable Stock is obtained from an Atlantic surfclam population dynamics model that includes growth, recruitment, and mortality to provide an estimate of biomass (yield) available to the fishery. Removal of the fishable biomass (Fishing) depends on the memory, searching, and communication skills of vessel captains. The individual fishing vessels are made up of specific vessel types, with home port locations (Fishing Fleet). The fishing fleet disperses from its home port, providing spatial distribution of fishing effort and in the acquisition of the allowed fishing quota. The landed fishing quota determines the economics of individual processing plants (Economics). External forces that modify the individual components and between-component interaction are offshore wind energy areas (Multiple Ocean Users), climate-related warming of bottom temperature and seasonal weather (Climate & Weather), species overlap with other clam stocks (Biological Interactions) which affects the ability to fish, and management decisions that modify the fishable quota (Management). These components of *SEFES* are represented by detailed processes that govern interactions within a component and between components (Figure 3). Data from the Atlantic surfclam stock assessment surveys and management council, fishery-dependent data, and guidance from Atlantic surfclam industry and management representatives provided inputs for the development and implementation of *SEFES* as well as for verification of simulations.

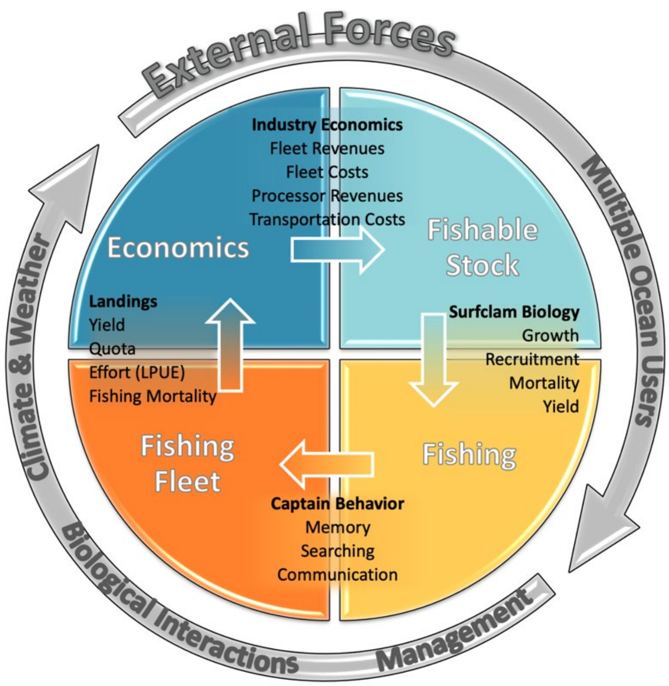
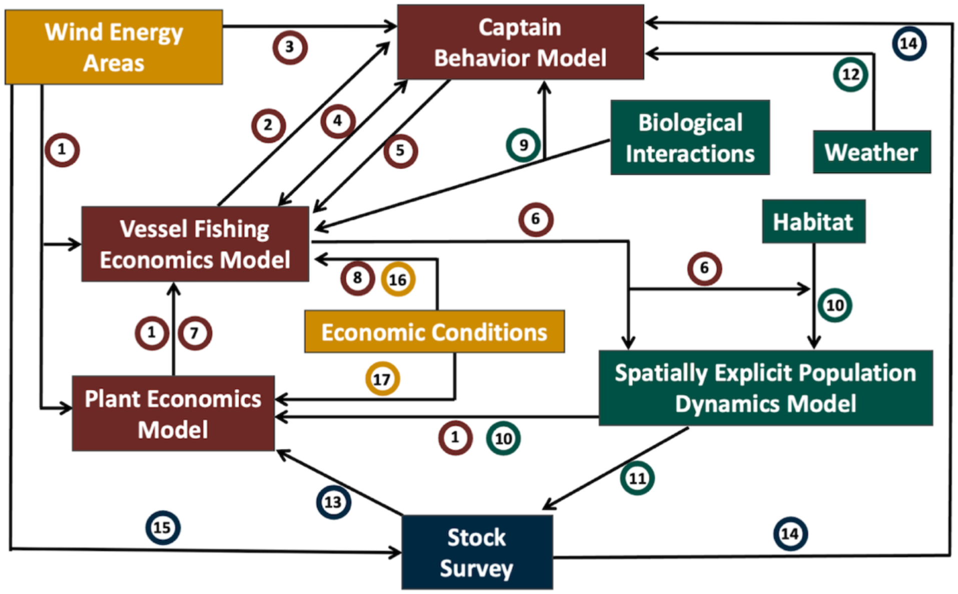


Figure 2: Components included in *SEFES.*
Components represent the Fishable Stock (light blue), Fishing (yellow), Fishing Fleet (orange) and Economics (dark blue). The primary processes that determine each component and links between components (black text at intersection of colored pies) and the external forces that affect all model components (outer circle) are shown. Details of *SEFES* used in this report are also provided in Figure 3.



Processes	Components	Property	Source
Fishery			
1	Fleet dispersion	Location and movement	Fishery dependent data & stock assessment
2	Vessel characteristics: speed & capacity, dredge size & efficiency	Speed (knots), capacity (cages), dredge size (length), dredge efficiency (rate of catch)	Industry advice & stock assessment
3	Safe vessel operation	Subjective	Industry advice
4	Captain memory, searching & communication	Catch (LPUE) per TMS	Industry advice
5	Captain skill	Rate of catch	Industry advice
6	Fishing mortality (size-selective)	Rate of catch by size class	Stock assessment
7	Vessels in the fleet, quota allocation	Number and properties of vessels, and quota (bushels)	Industry advice & fishery dependent data
8	Port location	Location (TMS)	Fishery dependent data & stock assessment
Biological & Environmental			
9	Species overlap	Location (TMS)	Industry advice & unpublished research data
10	Biological processes: recruitment, mortality, growth, yield	Recruitment (clams per m2), mortality (natural mortality rate), growth (shell size over time), yield (mass per size over season)	Industry advice, stock assessment, & unpublished data
11	Population structure	Length frequency and abundance by TMS	Stock assessment
12	Wind & temperature	Wind (miles per hour), temperature (°C)	Meteorological & airport records
Management			
13	Quota, stock trends, & fishery independent data	Quota (bushels), trends (abundance and size over time), fishery independent data (catch statistics)	Stock assessment, MAFMC 2020, research papers
14	Survey Report	Stock distribution and biomass by TMS	Stock assessment
15	Survey displacement	Location and movement	Advisor advice
External Forces			
16	Fuel & vessel costs	Rates	Industry advice & published prices
17	Wholesale value	Prices by product type	Industry advice

Figure 3: Detailed structure and interactions of *SEFES*.
Structure and interactions among fishery components (red boxes), biological and environmental components (green boxes), management component (blue box), and external forces (gold boxes) included in *SEFES*. The processes that determine transfers and connectivity between the model components are shown on the arrows with circled numbers. The process, property, and source of data are listed for each number in the lower table.

The population dynamics model included in Fishable Biomass component simulates the change in number (surfclams m^{-2}) and size distribution (1-cm shell length intervals) of Atlantic surfclams. Spatially explicit growth and mortality rates (Figure 4a) estimated from stock assessment observations were imposed, allowing observed gradients in Atlantic surfclam size, growth rate, and abundance to emerge in the simulations. Recruitment is defined using Beverton-Holt stock recruit dynamics (Beverton and Holt, 1993) with parameters based on stock assessment observations (NEFSC, 2022) and detailed evaluations of recruitment as influenced by post-settlement mortality (Timbs et al., 2019).

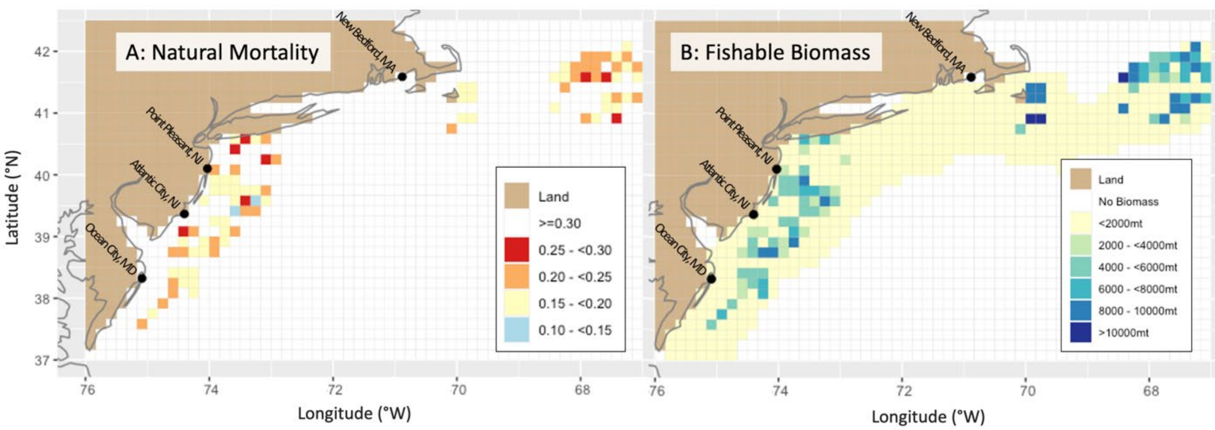


Figure 4: Map of surfclam mortality and biomass in the *SEFES* model domain.
Map of the model domain and locations of Atlantic surfclam fishing ports (black dots). The model domain is composed of 10' latitude by 10' longitude (about 10 NM on each side) rectangular squares (TMS), with 54 cells east-west across the shelf and 33 cells north-south. A) Spatial distribution of natural specific mortality rate (yr^{-1}) input to the Atlantic surfclam population dynamics model. B) Average annual distribution of fishable (>120 mm shell length) Atlantic surfclam biomass (metric tons, mt) obtained from the *SEFES* population dynamics (Figure 2, pg.6). The land areas (tan) and coastline (black line) are indicated.

The active agents in *SEFES* are the captains (Fishing component) and fishing vessels (Fishing Fleet component). Each Atlantic surfclam fishing vessel (Fishing) is controlled by a captain with specified characteristics that determine where and how efficiently the vessel harvests the fishable Atlantic surfclam biomass (Figure 4b). The captain's memory, and communication and searching skills were specified using information provided by Atlantic surfclam fishing captains to ensure that the model decisions reflect those made in the real fishery (Smajgl and Barreteau, 2017).

The characteristics assigned to fishing vessels (Fishing Fleet) determine speed, Atlantic surfclam harvest rates, landing capacities, and costs and are based on those associated with vessels in the actual fishing fleet. Vessels move around the model domain and harvest Atlantic surfclams based on decisions by each captain that are constrained by the operating characteristics of the vessel, such as speed, maximum time allowed at sea, and imposed harvest quota, as well as the knowledge base of the captain which integrates previous experience with natural fishing ability.

The simulated Atlantic surfclam harvest is purchased by specific processing plants associated with the home port of the fishing vessel. The economic processes and interactions (Economics) simulate revenues and costs for fishing vessels, processors revenues, and costs of transportation of landed catch from docks to processors. The simulated economic configurations of vessels and the processing sector are used to evaluate the effect of placement of offshore wind energy arrays on the overall economic conditions of the Atlantic surfclam fishery.

3.2 Surfclam Biology

The implementation of the Atlantic surfclam population dynamics model was based on data and observations that describe the current conditions, 2016 to 2019, of the stock and fishery. This restriction in time allows the model to reflect the contemporary stock and prevent bias by the shift in Atlantic surfclam range over recent decades (Hofmann et al., 2018; Hennen et al., 2018). Conversely, these simulations of the contemporary fishery do not reflect the possibility of future shifts in stock distribution that may occur.

3.2.1 Atlantic surfclam length, wet weight, and growth

The Atlantic surfclam population dynamics model uses 18 length classes, specified at 10-mm intervals between 20 and 200 mm. The average length for a category is the average of the lengths on either edge of the length class, e.g., the first interval includes all Atlantic surfclams between 20 and 30 mm in length and has an average length of 25 mm.

The average wet weight (W, grams) for Atlantic surfclams is obtained from an allometric relationship of the form:

$$W = aL^b \tag{1}$$

using the average length (L, mm) for each size category. The allometric parameters, $a = 5.84 \times 10^{-6}$ g mm^{-1} and $b = 3.098$, are specified using values given in Marzec et al. (2010). The wet weights are used with the length data obtained from the simulated stock surveys to estimate Atlantic surfclam stock biomass.

A daily growth rate for each Atlantic surfclam size class was calculated from the von Bertalanffy age-length relationship (von Bertalanffy, 1938) given by:

$$L = L_{\infty}\left(1 - e^{-kA}\right) \tag{2}$$

where L is length (mm), L_{∞} is the largest length (mm), k is the specific growth rate (yr^{-1}), and A is age (years). The length, maximum length, and age data were obtained from the Atlantic surfclam stock assessment survey (NEFSC, 2022). Data provided by Mann (unpubl. data) and Munroe et al. (2013) were used to estimate growth rate (k) using a nonlinear curve fitting routine. The growth rate, as length change per time, was estimated for each length interval from the age of the Atlantic surfclam at the lower bound of the interval and the length of the surfclam one year younger for each Ten-Minute Square (TMS). The one-year length change (mm yr^{-1}) divided by the length change over the interval determines the rate at which Atlantic surfclams move to the next length interval. The von Bertalanffy parameters were adjusted so that the Atlantic surfclams reached the largest lengths routinely encountered (~ 190 mm) in some locations in the model domain. Smaller local maximum lengths were obtained by varying the mortality rate, as described below.

3.2.2 Atlantic surfclam reproduction and recruitment

Atlantic surfclams recruit to the simulated population once per year on 1 October, about 4.5 months post-spawning in the spring, and 1-month post-spawning in the fall (Ropes, 1968). A stock-recruitment relationship is not available for Atlantic surfclams, so a standard Beverton-Holt relationship was used (Beverton and Holt, 1993). The total number of recruits was estimated from the total population biomass assuming a steepness of 0.8, following Myers et al. (1999) and O'Leary et al. (2011). Interannual recruitment variability was imposed by adding individuals (recruits) to the smallest length interval (20 - 30 mm) based on a random draw from a negative binomial distribution, which provides a patchy distribution among each TMS. The smallest length interval is consistent with juvenile growth rates that result in newly settled Atlantic surfclams reaching 20 mm by the end of the settlement year (Chintala and Grassle, 1995; Ma, 2005; Acquafredda et al., 2019).

3.2.3 Atlantic surfclam mortality

Mortality rate varies along the MAB shelf (Weinberg, 1998), which imposes spatial variability on Atlantic surfclam abundances. Recruitment is assumed to occur everywhere in the model domain, which is consistent with the observed wider geographic distribution of recruits relative to adults (Timbs et al., 2018) and with simulations from Atlantic surfclam larval transport models (Zhang et al., 2016). However, fishable populations of Atlantic surfclams do not occur over much of the model domain (cf. Figure 4b, pg.8) because the mortality rate is sufficiently high to prevent development of populations of harvestable size. This mortality gradient, which is driven by habitat suitability, was simulated by specifying a background mortality rate over the model domain that was then modified for each TMS. The background mortality was set at 1.5 yr^{-1} (Weinberg, 1998), limiting Atlantic surfclam survival to about 3 years. For TMSs with high (fishable) Atlantic surfclam densities based on the federal stock assessment survey data, mortality rates lower than this background mortality rate were estimated based on abundance or age data from the stock assessment survey (NEFSC, 2022).

The specific mortality rate based on abundance ($Mortality_{abundance}$) was then obtained using a hyperbolic tangent (*tanh*) function of the form:

$$Mortality_{abundance} = 0.5\left(1 - \tanh\left(\frac{D_{TMS} - D_0}{D_r}\right)\right) + m_{base} \tag{3}$$

where D_{TMS} is the observed density of Atlantic surfclams in each TMS, D_0 is a target density (0.2 Atlantic surfclams m^{-2}), D_r is the density range that allows maximum density (0.1 Atlantic surfclams m^{-2}) and m_{base} is the average base mortality (0.15 yr^{-1}) used in the stock assessment (NEFSC, 2022).

The specific mortality rate based on animal age ($Mortality_{age}$) for an individual TMS was also estimated using the Atlantic surfclam with the oldest age, as determined from the stock assessment survey, from the relationship given in Hoenig (1983) as:

$$Mortality_{age} = \frac{-\ln\left(age_{perc}\right)}{age_{max}} \tag{4}$$

Where age_{max} is the oldest observed surfclam in a TMS and age_{perc} is the percent of the population that survives to that oldest age, which was assumed to be 1% following Hoenig (1983).

Abundance-based mortality estimates can overestimate mortality if recent recruitment is low, or the stock is under-sampled (Wang and Jiao, 2015). Age-based mortality estimates can be biased if certain ages are under-sampled relative to their frequency in the population (Ricker, 1969). Thus, the estimates obtained from equations (3) and (4) were combined to obtain a mortality rate for each TMS as follows. Abundance- or age-based estimates were used for TMS for which only one of the rates was available. The lower of the two rates was used for TMS for which both estimates were available. For TMS without abundance or age-based rates, mortality rate was calculated from an average of the rates in two or more neighboring TMS. Surfclam natural mortality was imposed at the end of the simulation year and was the same across all length classes.

3.2.4 Atlantic surfclam meat yield

Meat yield depends on the time of year and the TMS. Yield is measured as usable meat and is about 75% of the total wet meat weight (Powell et al., 2015). The actual yield depends on the time of year because Atlantic surfclam meats are heavier in late spring through early fall during the spawning season (Ropes, 1968; Jones, 1981; Spruck et al., 1995). This seasonal variation in meat yield was imposed using a 5th order polynomial of the form:

$$YieldScale_i = -0.003411 + 1.18\left(\frac{i}{365}\right) + 24.06\left(\frac{i}{365}\right)^2 - 82.28\left(\frac{i}{365}\right)^3 + 88.46\left(\frac{i}{365}\right)^4 - 31.41\left(\frac{i}{365}\right)^5 \quad (5)$$

that scales meat yield by day of the year (i) to vary between 5 to 7 kg of Atlantic surfclam meat per bushel. The minimum and maximum yield estimates are based on ranges provided by the Atlantic surfclam industry. The yield curve is based on seasonal catch records provided by the Atlantic surfclam industry to allow incorporation of yield into economic planning. The weight of meat in a bushel that is landed is scaled by the yield curve so that seasonal changes in meat weights supplied to processors are included in the simulations.

3.3 Captain Behavior

Characteristics associated with the captains of each simulated fishing vessel include searching behavior, differential use of information in older logbooks to inform fishing location decisions, skill at fishing, and a range of tendency to communicate with other captains. Relationships used to describe a captain's decision-making process when planning a fishing trip, constraints imposed by landing deadlines and weather, and the tendency to gain or share information about surfclam abundance were obtained from inputs provided by Atlantic surfclam fishery captains and other industry representatives (Smajgl and Barreteau, 2017). Details of these are provided in the following sections.

3.3.1 Captain Memory

The captain controls when, where, and how a fishing vessel operates. Information on how a captain makes these decisions is based on memory of past fishing trips, which varies for individual captains. The simulated captain's memory log includes an expected landings per unit effort (LPUE), specified in cages of catch per hour for every fishable TMS in the model domain. At the beginning of a simulation, the distribution of fishable Atlantic surfclam abundance for each TMS is known by every captain (cf. Figure 4b, pg.8). That is, initially, all captains have omniscient information. At the end of each fishing trip, the catch history in the captain's memory log is updated for the TMS that was fished. In reality, a captain of an Atlantic surfclam fishing vessel is not restricted to a single TMS and often fishes across more than one TMS on a single trip. This information was included in the simulated captain's memories by updating the memory log with the LPUE in a randomly selected TMS adjacent to the one that was fished for 80% of the captain's fishing trips. This approach ensures that the captain's memory of the entire domain is updated or outdated over time depending on the TMS that is fished and changes in the Atlantic surfclam population distribution. The captain uses memory of the LPUE across all TMSs in selecting areas to fish on subsequent trips. Final selection of the target TMS for fishing is obtained by minimizing the sum of fishing time required to fill the hold capacity of the fishing vessel and inbound travel time (steaming time).

Observations and information provided by captains of Atlantic surfclam fishing vessels indicated that captains keep detailed logs of their fishing activities, thereby providing an extensive history of fishing experiences that is used to make decisions about where to fish. The relevance of this information can be expected to decrease over time as fishing, recruitment, and natural mortality change the distribution and abundance of the surfclam stock. Nonetheless, a captain may still use older information to make decisions. This reduction in information relevance was included by assigning each simulated captain a memory weight factor that emphasizes new or old information in the memory record. After fishing in a certain TMS and returning to port, the LPUE for that fishing trip is used to update the information in the captain's memory record and a memory factor that specifies the weight to be placed on recent LPUE information is applied. The updated memory of LPUE (M_{LPUE}) in fished TMS is based on a memory factor (f), the previously remembered LPUE (Old_{LPUE}), and the new LPUE (New_{LPUE}) for that TMS as:

$$M_{LPUE} = f Old_{LPUE} + (1 - f) New_{LPUE} \tag{6}$$

A memory factor of 0.5 indicates that the memory retained is the average of the previously stored and new LPUEs. The captain's memory, but not the memory factor, varies over time during the simulation. In simulations, a captain memory can be assigned memory weight factors ranging from 0.2 to 0.99 which allow memories to be biased towards new or old information, respectively. Memory weights of 0.2 and 0.8 place emphasis of using information from the previous 1 to 6 weeks, respectively, to make decisions about fishing. Memory weights of 0.98 or 0.99 bases fishing decisions on performance over 7 months to over 1 year, respectively (Powell et al., 2015).

3.3.2 Captain searching

Inputs from Atlantic surfclam fishery captains and other industry representatives about the frequency and nature of searching for new fishing grounds provided the basis for implementing options for the simulated fishing vessel captains to spend time at sea searching for new fishing locations. On a percentage of the fishing trips, a captain will search for new fishing grounds by targeting a random TMS within a 6-hour steam of the homeport that is independent of the captain’s memory of past LPUE performance in that TMS. The percentage of trips during which a captain will search is defined for each captain for each simulation. Catch rate in the TMS that was searched is then updated in the captain’s memory. The purpose of the random searching (for real captains and simulated captains) is to identify unknown areas containing surfclams. The random search only includes TMS grid cells that are defined as surfclam habitat. This constraint prevents the captains from searching in areas with unsuitable habitat or that are too deep.

3.3.3 Captain communication

Information sharing among surfclam fishing vessel captains affects time spent fishing, catch, and landings. The level of communication among fishing vessel captains can range from no information sharing to limited or total information sharing. Inputs from Atlantic surfclam fishery captains about how often, with whom, and the type of fishing information that is shared with other captains suggested that information sharing about fishing trips occurs primarily among captains from the same company and the same home port. Information sharing was less among captains from different companies but same home port and even less among captains from different companies and home ports. These inputs were incorporated into the captain’s behavior using a probability distribution that allows captains from the same company and the same port to share 75% of information about fishing trips. Captains sharing the same home port, but from different companies, share 50% of information, and captains from different ports share only 25% of information.

3.4 Fishing Vessels

The simulated fishing fleet was specified to reflect the range of vessels and capacity in the present day Atlantic surfclam fishery using information provided by industry representatives, vessel owners, and operators. The simulated fleet consists of 33 fishing vessels, each with individual specifications for dredge width, catch capacity, steaming speed, fuel consumption, and home port location (Table 1). Most of the simulated fleet has a home port in Atlantic City, NJ (19 vessels) and New Bedford, MA (11 vessels). The remaining three vessels were assigned to Ocean City, MD (2 vessels) and Point Pleasant, NJ (1 vessel). The simulated fleet was grouped into vessel size classes based on hull length categorized as small (≦79 feet: 11 vessels), medium (80 - 94 feet: 10 vessels), large (95 -110 feet: 8 vessels), and jumbo (>110 feet: 4 vessels). Atlantic surfclams are caught with a hydraulic dredge at a rate (cages per hour, capped at 10 cages per hour) that scales with the density of market-size surfclams in the TMS. The simulated catch is apportioned into standardized cages, each of which holds 32 bushels of surfclams (1 bushel = 53.2 L). Each vessel has capacity to hold a specific number of cages when fully loaded (Table 1).

Table 1: Vessel characteristics by category of the simulated fishing fleet.

Vessel Category	Hull Length (feet)	Number of Vessels	Average Cage Capacity	Average Vessel Steaming Speed (knots)	Average Dredge Width (m)	Wind Conditions Preventing Fishing (knots)
Small	≦79	11	31	8.7	2.3	>10
Medium	80 – 94	10	54	9.0	3.3	>15
Large	95 – 110	8	66	9.5	3.7	>15
Jumbo	>110	4	140	10	4.6	>20

For the simulations, fishing vessel activity is configured such that individual vessels either wait at the homeport, steam to and from a fishing location, or actively fish for Atlantic surfclams. Processing plants distribute quota to each vessel on a weekly schedule that allows vessels to make 2 fishing trips per week. The choice of vessel activity is made each hour and continues for the remainder of the hour and total time spent in each activity is tracked in the simulations. Vessel movement is based on waypoints that prescribe a path to follow to each possible fishing location. The waypoint calculation includes information about the TMSs occupied by land, other obstructions (e.g., wind energy areas), ports, and Atlantic surfclam habitat. Paths from each port to each TMS with Atlantic surfclam habitat are calculated with the A* (A Star) path algorithm (Hart et al., 1968), which finds the shortest path between two locations in two dimensions, avoiding squares where transit is not allowed (e.g., land, wind energy areas). A path-finding module in MATLAB (Premakurmar, 2021) that includes TMS locations and an overlay of no-transit TMSs, calculates a list of TMSs that define the path to follow between the two locations; defined paths are truncated to remove points connected by a straight line between two base points. The resultant waypoint file contains a set of points to traverse from each port to each TMS with Atlantic surfclam habitat. Pre-calculation of transit routes follows a minimum distance path, which reduces simulation time required to find an optimal fishing location.

3.4.1 Weather

Weather determines if and when Atlantic surfclam fishing is feasible and safe. Weather control on fishing is implemented using relationships between wind speed and boat size that prevent a vessel from leaving port under certain weather conditions. Wind speed and direction were obtained for 2015-2019 from meteorological buoys deployed along the MAB (NOAA National Data Buoy Center) and used to calculate the probability of winds in specified speed ranges, a measure of weather conditions. Weather on a specific simulation day was related to conditions two days later by a random draw from the calculated wind speed probability for that day and season. This provides a forecast that is used to decide if a vessel should leave the dock. Wind forecasts of >10 knots, >15 knots, and >20 knots prevent small vessels, medium and large vessels, and jumbo vessels, respectively, from leaving port to fish for surfclams (Table 1). The same weather conditions were imposed to force boats to stop fishing and return to the dock, sometimes without acquiring a full load of Atlantic surfclam catch (Table 1).

A practice in the fishery is to stack live Atlantic surfclams on the deck (i.e., deck load) for transport to the home port rather than placing the catch into refrigeration units. The deck-loaded catch can spoil when air temperatures are high (>25°C) and transit time back to the dock after fishing begins is too long (>30 hours). This effect was included in the simulations using a seasonally varying air temperature factor that forces fishing boats to avoid catch spoilage by returning to port earlier when air temperatures rise in the summer. Seasonally varying air temperature distribution was calculated from meteorological observations reported from airports nearest to each New Jersey port (Cape May International, Atlantic City International, Ocean County Airport); port locations for which spoilage of deck-loaded catch is a concern. The minimum (summer) and maximum (winter) trip duration scales with the monthly air temperature factor to constrain the trip length seasonally. Both weather and time limits on certain trips can cause vessels to return to port without filling to full capacity (Table 1).

3.5 Industry Economics

The economic component included in *SEFES* (Figure 2, pg. 6) was used to simulate revenues and costs for fishing vessels and processors and was developed in collaboration with Atlantic surfclam industry members representing four major seafood companies that purchase and process 80-90% of Atlantic surfclam landings (Atlantic Capes Fisheries, La Monica Fine Foods, Sea Watch International, and Surfside Foods; estimate based on vessel trip report data described below). Discussions with captains of eleven Atlantic surfclam fishing vessels provided information on fishing strategies and decision-making processes, vessel costs, and vessel maintenance schedules. Additional information about fishing vessel costs related to maintenance and insurance were provided by a representative from one major seafood company for seven vessels in the Atlantic surfclam fishing fleet. Summary data of responses by captains of Atlantic surfclam and ocean quahog fishing vessels to a 2011 cost survey administered by the Northeast Fisheries Science Center (NEFSC) were provided by the NEFSC's Social Sciences Branch and used to assess economic parameterizations. Vessel trip reports from 2015-2019 for the 33 Atlantic surfclam fishing vessels that makeup the fishing fleet (Table 1) were obtained from NOAA Fisheries' Greater Atlantic Regional Fisheries Office (GARFO, 2021). These data were used to verify simulated fishing behavior and Atlantic surfclam catch rates (see Chapter 4), and to assess the economic parameterizations used in this analysis.

3.5.1 Fleet Revenues

Landings revenues for fishing vessel, i, at time, t, ($R_{i,t}$) were calculated as:

$$R_{i,t} = Cages_{i,t}\,CagePrice \tag{7}$$

where $Cages_{i,t}$ is the number of cages of Atlantic surfclams landed by fishing vessel i at time t obtained from simulations that included fishing (see Chapter 4). The ex-vessel price per cage landed (*CagePrice*) was based on average annual bushel prices from 2017 to 2019 obtained from the 2020 stock assessment report (NEFSC, 2022) and using the industry conversion of 32 bushels (1 bushel = 53.2 L) per standard cage (i.e., 60 cubic feet). The gross domestic product (GDP) implicit price deflator (US BEA, 2021) was used to adjust prices for 2017 and 2018 to 2019 dollars. The parameter *CagePrice* was set equal to the three-year landings-weighted average price of USD 458.75 cage^{-1} (2019 dollars). Atlantic surfclam ex-vessel prices are highly inelastic because the majority of processed product is purchased by a small number of large consumer goods companies who can easily substitute imported clams (Mitchell et al., 2011; Northern Economics, 2019). Thus, a fixed price was used for all simulations.

3.5.2 Fleet Costs

Information provided by Atlantic surfclam fishing vessel captains indicated trip supplies were typically minimal and that the crew members covered their expenses related to food, water, and other provisions. Costs related to equipment purchases, vessel payments, and business expenses were not considered due to the level of vertical integration in the industry and because industry members indicated that these costs were not frequently considered as operational costs for the fishing fleet. Therefore, the costs associated with operating each Atlantic surfclam fishing vessel consisted of captain and crew share ($C_{i,t}^{share}$), fuel costs ($C_{i,t}^{fuel}$), vessel and gear maintenance expenses ($C_{i,t}^{maint}$), insurance ($C_{i,t}^{insur}$), and costs related to quota ($C_{i,t}^{quota}$), specified as:

$$C_{i,t}^{share} = fr\,R_{i,t} \tag{8}$$

$$C_{i,t}^{fuel} = FuelPrice_p\left(Hr_{i,t}^{steam}\,FuelSteam_i + Hr_{i,t}^{fish}\,FuelFish_i\right) \tag{9}$$

$$C_{i,t}^{maint} = (MjrMnt_t\,TSurf_i) + (RegMnt_i\,NTrip_{i,t}) \tag{10}$$

$$C_{i,t}^{insur} = \left(HulIns_{i,t} + (PIIns_t\,NCrew_i) + OtherIns_t\right)TSurf_i \tag{11}$$

$$C_{i,t}^{quota} = Cages_{i,t}\,QuotaPrice \tag{12}$$

The total costs for an Atlantic surfclam fishing vessel at time, t, ($TC_{i,t}$) were the sum across share, fuel, maintenance, insurance, and quota costs:

$$TC_{i,t} = C_{i,t}^{share} + C_{i,t}^{fuel} + C_{i,t}^{maint} + C_{i,t}^{insur} + C_{i,t}^{quota} \tag{13}$$

Crew and captain share costs for vessel, i, at time, t (equation 8) were specified as a fixed fraction, fr, of gross revenues estimated from equation (7). The parameter fr was set to 0.3 based on information provided by Atlantic surfclam fishing vessel captains and industry representatives. Some captains indicated payments were a fixed dollar value per bushel while others were paid as a percentage of gross revenue, e.g., 7% per crew member and 9% for the captain, with the captain share being typically 30% more than a crew share. Fixed dollar values and individual revenue shares were approximately 30% of gross revenues for a crew of three and one captain, which is standard in the Atlantic surfclam fishery. This crew share estimate is similar to that discussed in Brandt and Ding (2008), particularly when the vessel owner also owns quota used for the trip, which is common in the present fishery given the high level of vertical integration.

Fuel consumption (L hr^{-1}) while steaming, $FuelSteam_i$, and fishing, $FuelFish_i$, were provided by the Atlantic surfclam industry for each vessel included in the model (Table 2). Fuel consumption rates were applied to the total hours spent steaming ($Hr_{i,t}^{steam}$) and fishing ($Hr_{i,t}^{fish}$) obtained from a fishing simulation (see Chapter 4) to calculate total fuel use for each simulated vessel during a particular time period. Fuel cost (equation 9) was then determined using fuel prices ($FuelPrice_p$) that varied by port, p (Table 3). Fuel prices were based on annual average prices for New England and Central Atlantic regions provided by the Energy Information Administration for years 2017-2019 (EIA, 2021), adjusted for inflation.

Table 2: Fishing vessel economic characteristics by category*.

Vessel Category	Crew Size (number)	Fuel Steam (L hr^{-1})	Fuel Fish (L hr^{-1})	Targeted Trips (%)
Small	3.55	86.38	132.15	100.00
	0.52	*39.22*	*61.13*	*0.00*
Medium	3.60	138.92	190.41	86.00
	0.52	*42.62*	*41.34*	*30.00*
Large	4.25	198.28	287.69	71.00
	0.46	*49.44*	*98.23*	*41.00*
Jumbo	4.75	266.87	300.94	75.00
	0.50	*55.42*	*57.77*	*29.00*

*Crew size, fuel use when steaming and fishing, and the percent of targeted trips are shown as mean values and standard deviations (italics).

Table 3: Distribution of the vessels, processors, and fuel prices and average travel distances for processing.

Port Location	Vessels (number)	Processors (number)*	Fuel Price (USD L^{-1})**	Processing Distance (km)***
New Bedford, MA	11	2	$0.81	335
Point Pleasant, NJ	2	1	$0.85	167
Atlantic City, NJ	18	3	$0.85	129
Ocean City, MD	2	1	$0.85	266

* Two processing companies were associated with multiple ports
** Fuel prices based on region-specific averages provided by the Energy Information Administration (EIA, 2021)
*** Processing distance is the average distance in kilometers (km) between port of landing and associated processing plants used by the Atlantic surfclam fishing vessels landing at that port

The estimated maintenance costs for each Atlantic surfclam fishing vessel (equation 10) included fixed annual costs for major maintenance and repair ($MjrMnt_t$), such as haul-outs for painting, engine repairs, and vessel improvement, as well as regular maintenance ($RegMnt_i$), such as gear repair. Using information provided by Atlantic surfclam fishing vessel captains and industry representatives, and financial statements for seven vessels provided by one company, major maintenance costs were estimated to be about USD 150,000 every two and a half years per vessel (USD 60,000 yr^{-1} and USD ~1,154 $week^{-1}$). Major maintenance costs were adjusted based on the fraction of total annual trips taken by a fishing vessel that targeted Atlantic surfclams ($TSurf_i$), such that only a portion of annual haul-out costs were attributed to surfclam fishing. The proportion of total annual trips for each vessel targeting Atlantic surfclams was provided by industry representatives and verified using vessel trip report data (Table 2). Discussions with industry members, review of vessel financial statements, and evaluation of estimates cited previously in the literature (e.g., Kirkley et al., 2002, Das, 2014) indicated that regular maintenance costs, $RegMnt_i$, do not vary substantially for small ($\leq$ 79 feet), medium (80 - 94 feet), or large (95 – 110 feet) vessels, though might be higher for jumbo (> 110 feet) vessels. Therefore, a fixed value of USD 3,000 $trip^{-1}$ was used for small, medium, and large vessels while USD 5,000 $trip^{-1}$ was used for jumbo vessels. These values were multiplied by the number of trips taken by a vessel during time period t, $NTrip_{i,t}$, and added to major maintenance costs to obtain total maintenance costs for vessel, i, at time, t (equation 10).

Insurance cost estimates were determined following captain discussions, conversations with industry representatives, and evaluation of vessel annual insurance cost statements (n = 7 vessels). Annual hull insurance for each vessel, $HulIns_{i,t}$, was approximated at USD 10,000 yr^{-1} for small vessels, USD 20,000 yr^{-1} for medium and large vessels, and USD 60,000 yr^{-1} for jumbo vessels. Protection and indemnity insurance, $PIIns_t$, was estimated at a rate of USD 5,000 per crew member and scaled by the number of crew per vessel, $NCrew_i$ (Table 2). Additional insurance related to excess liability for crew and pollution coverage, $OtherIns_t$, was estimated to be about USD 10,000 yr^{-1} for each vessel, independent of vessel or crew size. The sum of the costs for hull, protection and indemnity, and additional insurance was scaled by the fraction of annual fishing trips targeting Atlantic surfclams ($TSurf_i$) as insurance is paid out annually and shared across trips targeting different species (equation 11).

Industry members indicated prices associated with leasing quota have varied between USD 3 $bushel^{-1}$ and USD 5 $bushel^{-1}$ over the past decade, with recent average quota lease prices closer to USD 3 $bushel^{-1}$. This value was used as the lease price (*QuotaPrice*), that was scaled by the number of cages landed by vessel, i, at time, t, ($Cages_{i,t}$) to calculate the quota cost (equation 12). Quota ownership data are publicly available, but this information is not easily linked to vessel ownership. In this analysis, quota costs represent either a realized business expense or an opportunity cost, depending on whether or not quota for a trip's landings was owned by the vessel owner. Industry members described quota costs as a key financial consideration and operational constraint. Therefore, independent of ownership, quota costs for all landings are included here in assessing vessel financial performance.

Total landings, time spent steaming and fishing, and the number of trips were calculated by vessel and year using vessel trip reports (n = 6,830 trip observations from 2015-2019 for 33 vessels; GARFO, 2021). These fishing activity measures were then used with the economic parameterization (equations 7-13) to assess annual average costs and revenues by vessel size class (Table 4) as well as to compare cost estimates with data provided by the NEFSC's Social Sciences Branch (Table S1, pg. 56). Fuel costs represented the largest expense for medium, large, and jumbo vessels, while for small vessels maintenance costs were dominant. Total costs exceeded revenues for small, medium, and large vessels and were nearly equal for jumbo vessels. Negative profit margins are reasonable here given the vertical integration in the industry and suggest that vessel operations are routinely subsidized by the processing sector. Annual cost estimates based on the parameterization presented here were similar to 2011 data collected by the NEFSC (Table S1, pg. 56). The sensitivity of profit margins by vessel size class was explored with three alternative economic parameterizations: a high-cost parameterization, where fuel and insurance costs were increased by 25%; a low-cost parameterization, where quota costs were removed and maintenance costs reduced by 25%; and a high-price parameterization, where ex-vessel bushel prices were increased by 25%. Average profit margins were variable though largely negative across the range represented by these economic parameterizations (Table S2, pg. 56).

Table 4: Annual cost and revenue estimates (2019 USD) for each vessel size class.*

Vessel Category	Share (USD)	Fuel (USD)	Maintenance (USD)	Insurance (USD)	Quota (USD)	Total Costs (USD)	Revenues (USD)
Small	164,119	202,588	217,596	38,191	114,448	736,942	547,062
	132,105	*193,295*	*91,697*	*2,428*	*92,123*	*478,888*	*440,349*
Medium	239,496	302,442	220,617	42,924	167,013	972,492	798,320
	111,523	*175,079*	*87,356*	*11,878*	*77,770*	*422,326*	*371,743*
Large	167,171	321,703	174,329	39,181	116,576	818,960	557,235
	101,080	*244,501*	*117,501*	*16,724*	*70,488*	*512,037*	*336,934*
Jumbo	489,740	511,349	219,471	70,086	341,520	1,632,166	1,632,466
	213,166	*248,385*	*65,984*	*25,856*	*148,651*	*662,820*	*710,552*

* Values shown as mean values and standard deviations (*italics*).

3.5.3 Processor Revenues

Revenues for each processing company, *c*, at time, *t*, ($R_{c,t}^{proc}$) were calculated as:

$$R_{c,t}^{proc} = \sum_j \sum_{i,c} Weight_{i,t} \, (1 - MeatLoss) \, ProductFrac_{c,j} \, WhsPrice_j \tag{14}$$

where $Weight_{i,t}$ is landings in kilograms of usable meat weight by vessel, *i,* at time, *t*, obtained from fishing simulations (see Chapter 4). The amount of useable meat per bushel varied with Atlantic surfclam size and season (Powell et al., 2015; Munroe et al., 2022). A fixed fraction (*MeatLoss*) of the landed usable meat is lost during processing, which was set at 15% based on information provided by industry representatives and loss estimates contained in Barker and Merrill (1967) and Loesch (1977). The total production for each processing company consists of three product types, *j*, that include fresh, frozen, and canned products. The fraction of total production for each processing company of each product type ($ProductFrac_{c,j}$) was specified using information provided by company representatives. Landings information from vessel trip reports together with confidential product breakdowns for each processing company suggested that 20-25% of landings are processed as fresh products, 40-45% as frozen, and 30-

35% as canned, though considerable variation existed among individual processors. The wholesale price charged for processed products after leaving the processing plant ($WhsPrice_j$) was specified based on information provided by industry members. Wholesale prices for clam products reported from the 2018 NMFS Annual Survey of U.S. Seafood Processors were around USD 2-4 kg^{-1} (NMFS, 2018). These prices were reported in terms of final product weights rather than by the quantity of processed Atlantic surfclam, making it difficult to adjust to prices in terms of Atlantic surfclam amounts. Additionally, reported prices do not distinguish between Atlantic surfclams and ocean quahogs, the latter being processed into generally lower-value products. Industry members indicated that while differences existed in product prices resulting from a variety of value-added steps in processing, little differentiation exists in final product price per kg of Atlantic surfclam used, which was typically USD 8.80-11 kg^{-1}. A fixed price of USD 9.92 kg^{-1} for all processed Atlantic surfclam products was therefore used to specify $WhsPrice_j$ in equation (14). Total revenues for each processor are then the sum of revenues across product types landed by fishing vessels associated with the processing company (equation 14).

3.5.4 Processor Transportation Costs

Transportation costs for each processing company, *c*, at time, *t*, ($C_{c,t}^{trans}$) were calculated as:

$$C_{c,t}^{trans} = \sum_{i,c} Cages_{i,t}\, Distance_{i,c}\, FreightRate \tag{15}$$

where $Cages_{i,t}$, is the number of cages landed by vessel, *i*, associated with a processing company, *c*, at time, *t*, $Distance_{i,c}$ is the distance in kilometers between the port of landing for vessel, *i*, and processing facilities for company, *c*, estimated using Google Maps (Table 3, pg. 16), and *FreightRate* is the estimated average freight rate in 2019 USD per kilometer per cage. Two companies used multiple ports and one company had multiple processing plants. For the company with multiple processing facilities, product flow from ports to plants was determined in consultation with a company representative and used to distribute $Cages_{i,t}$ across multiple plants. The value used to specify *FreightRate* was estimated from information contained in the American Transportation Research Institute's annual report (Williams and Murray, 2020) and from estimates provided by DAT Solutions, LLC, a large freight exchange service provider (DAT Solutions, 2020). The former reported an average marginal cost in the U.S. Northeast region of USD 1.22 km^{-1}, which included fuel cost, truck payments, repair and maintenance, licenses and permits, truck tires, tolls, driver wages and driver benefits (Williams and Murray, 2020). The rate reported by DAT Solutions, LLC was USD 0.98 km^{-1} for refrigerated trucks in the U.S. Northeast during 2020 (DAT Solutions, 2020). For this analysis, an average freight rate of USD 1.10 km^{-1} was used. Industry members indicated a standard haul was 14 cages, implying a freight rate per cage of USD ~0.08 km^{-1} $cage^{-1}$.

3.6 Management Submodel

The management component of *SEFES* is underpinned by the federal scientific survey conducted annually to determine the size and distribution of the Atlantic surfclam population. The management module uses the survey information to impose reference points and calculate the allowable biological catch (ABC) used to set the harvest quotas for the following year. An annual survey of the surfclam stock biomass is conducted in the model in October of each year. The survey is based on tows distributed throughout the simulated Atlantic surfclam stock in a stratified random design. The distribution of the strata in the model domain follows those used in the federal survey as defined in Jacobsen and Hennen (2019). The TMSs in the model domain that have >25% of their area within a given federal stratum were assigned to that survey stratum (Figure 5).

The simulated survey provided estimates of surfclam biomass and abundance. Tows were allocated to survey strata to acquire approximately 150 stations for a survey. The abundance estimate was assumed to have the same uncertainty as the federal Atlantic surfclam survey (coefficient of variation = 0.24, NEFSC, 2022). The simulated survey data were used to calculate the ABC, following the approach used by the regulatory agency that controls Atlantic surfclam catch quota (NEFSC, 2022). The model permits calculation of an ABC as standardly done by the Mid-Atlantic Fisheries Management Council Scientific and Statistical Committee (MAFMC SSC). If the catch level exceeds the ABC fishing would stop for the remainder of the year. However, the fishery operates under a quota cap of 3.5 million bushels of Atlantic surfclams that is imposed by a Fishery Management Plan (NEFSC, 2022), which the simulated catch never exceeds. Thus, the ABC does not affect the simulated fishery, as is true in the actual fishery. The survey also provides a biomass estimate as would be obtained under today's survey conditions. It is anticipated that the federal survey will be unable to perform survey tows within wind energy areas (Methratta et al., 2020). Therefore, in simulations for which wind energy areas are implemented, the survey can not access those areas and will not sample there. The survey will likewise reduce the available area it is estimating biomass for by subtracting all unavailable wind energy areas from the abundance estimates.

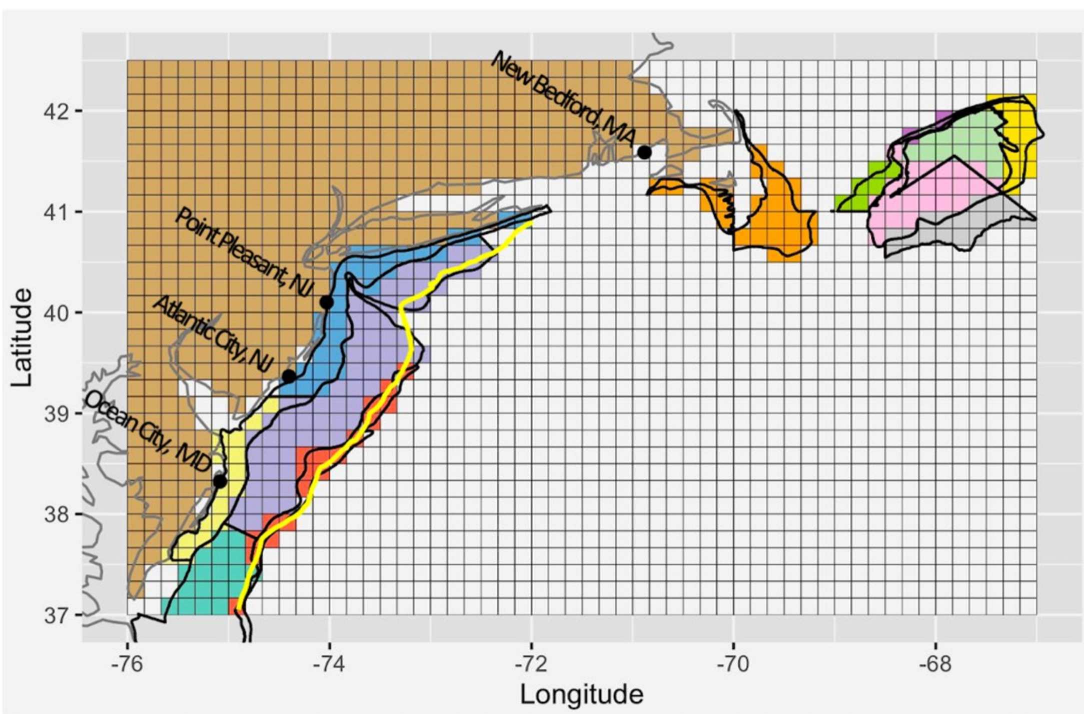


Figure 5: Map of surfclam strata in the *SEFES* model domain.
Map of the Mid-Atlantic Bight showing the model domain and locations of ports for the Atlantic surfclam fishing fleet (black dots). TMSs are colored for their assignment to various federal survey strata. True Atlantic surfclam strata boundaries are overlaid with black lines. The yellow line approximates the 40-m isobath where overlap with ocean quahogs has been reported.

3.7 Simulation Implementation

3.7.1 Model Domain

Each of the TMSs that make up the model domain have a north-south distance of 10 NM. The east-west distance of each square is fixed at the width determined by the central latitude of the grid. The TMS are categorized by depth which restricts access for some fishing vessels because of size and draft requirements (Table 1, pg. 13), i.e., regions too shallow for vessels or land areas. Large and jumbo vessels fishing out of New Bedford, MA are unable to fish on Nantucket Shoals because it is too shallow. Thus, the TMSs in this region were set to exclude the largest vessels in the fishing fleet. The location of ports and processing plants that are the primary landing sites for Atlantic surfclams are specified in the relevant land TMS (Figure 5).

Current federal regulations prohibit Atlantic surfclam fishing vessels from landing mixed-species catches, such as can happen in areas where Atlantic surfclams co-exist with ocean quahogs. In the overlap regions, the handling time of the catch is increased because fishers need to sort the catch, as a result fishing effort is typically relocated to avoid these areas. The areas where Atlantic surfclams and ocean quahogs overlap were identified using information provided by fishing vessel captains, and approximately follows the 40-m isobath. This overlap region was defined in the biological habitat of each TMS. The simulated vessels that fish in the overlap area accrue a penalty of lower catch efficiency. This penalty is subtracted from the captain's skill while fishing in the overlap area, making that captain 50% less effective at capturing Atlantic surfclams in any TMS that overlaps with ocean quahogs.

3.7.2 Initial Atlantic surfclam distribution

Initial biomass distribution, given as Atlantic surfclams m^{-2} per length class, was specified using a total population biomass that was distributed into each TMS as a total Atlantic surfclam density (summed over lengths) using a negative binomial random distribution to create a patchy distribution. A spatially-varying length distribution was then used to distribute the Atlantic surfclam biomass in each TMS into length intervals. The patchiness structure is maintained subsequently by recruitment, as described previously (see section 3.2.2).

3.7.3 Captain Types

Each captain of the simulated vessels was allowed to randomly search the model domain for Atlantic surfclams on 0%, 5%, or 10% of the fishing trips, and was assigned memory weights of 0.2, 0.8, 0.98 or 0.99. This results in a total of 12 captain types, who were randomly assigned to each of the 33 fishing vessels for each simulation. The captain-vessel assignments were randomized, and simulations were repeated 200 times which allows variability to emerge in the simulations. The simulation outputs were averaged to obtain estimates of average annual fishery metrics.

4 Model Validation

The focus of this Chapter is on simulation of fishing fleet behavior, and evaluation of the simulations with observations of fishing effort, distribution, and total landings. These analyses provide verification of a reference simulation that is the basis for projections of the economic and survey impacts of wind energy area placement on the Atlantic surfclam fishery, which are described in Chapters 5, 6, 7, and 8.

4.1 Reference Simulation Implementation

The population dynamics model was initialized with the Atlantic surfclam biomass distribution and run for 100 years without fishing to allow the population to come into equilibrium with the specified growth rates, mortality, and recruitment. This equilibrium simulation is the basis of the reference simulation that reproduced the unfished spatial patterns in Atlantic surfclam distribution. Fishing was then allowed for the next 200 years of simulation so that the model reached equilibrium with the fishery dynamics and reproduced the contemporary spatial patterns in Atlantic surfclam distribution. The last 50 years of simulation with fishing were used for analysis. Quantitative and qualitative approaches were used to assess the reference simulation results. These were done with inputs from surfclam industry representatives to ensure that simulations represented the current state of the fishery as reflected by current knowledge.

Observed annual Atlantic surfclam catch for 2015 to 2019 is reported as part of the annual stock assessment (NEFSC, 2022). Data on fishing vessel trips for 2015 to 2019 for the 33 vessels (6,830 total trips) that make up the actual Atlantic surfclam fishing fleet were obtained from the Greater Atlantic Regional Fisheries Office (GARFO, 2021). These data allow calculation of time at sea, catch in bushels, LPUE (cages per hour fished), and the fraction of cage capacity utilized for each fishing trip. Equivalent metrics were calculated from simulations for each simulated year and weekly vessel trips during the last 50 years of the 200 model runs (n=10,000 years, and n=11,623,095 weekly vessel observations). Quantitative comparisons of simulated and observed values were done using Mann-Whitney-Wilcoxon tests and boxplots to visually evaluate data overlap. Typically, the root mean square error (RMSE) is used as a measure of the differences between simulated and observed distributions (Willmott, 1981). However, the normalized root mean squared error (NRMSE), which is obtained by dividing simulated and observed values by observed trip-level averages, was used to calculate the fleet-, annual- and trip-level metric, which have varying units. Spatial patterns were also examined using qualitative comparisons of observed and simulated distributions of catch and effort; these qualitative features have been identified as important considerations that are often disregarded in favor of more quantitative analyses in these complex systems (Smajgl and Barreteau, 2017; Burgess et al., 2020).

4.2 Reference Simulation Verification

Simulated Atlantic surfclam biomass from the fishing simulation was similar to biomass estimates from the federal stock assessment (Figure 6A; p=1, W=50). The NRMSE of 0.10 indicates that simulated biomass closely matches observed biomass. The simulated average biomass of 0.82 million metric tonnes was intermediate between the two observed values of Atlantic surfclam biomass. The stock is not completely surveyed each year, which results in only two observed biomass values being available for 2015 to 2019.

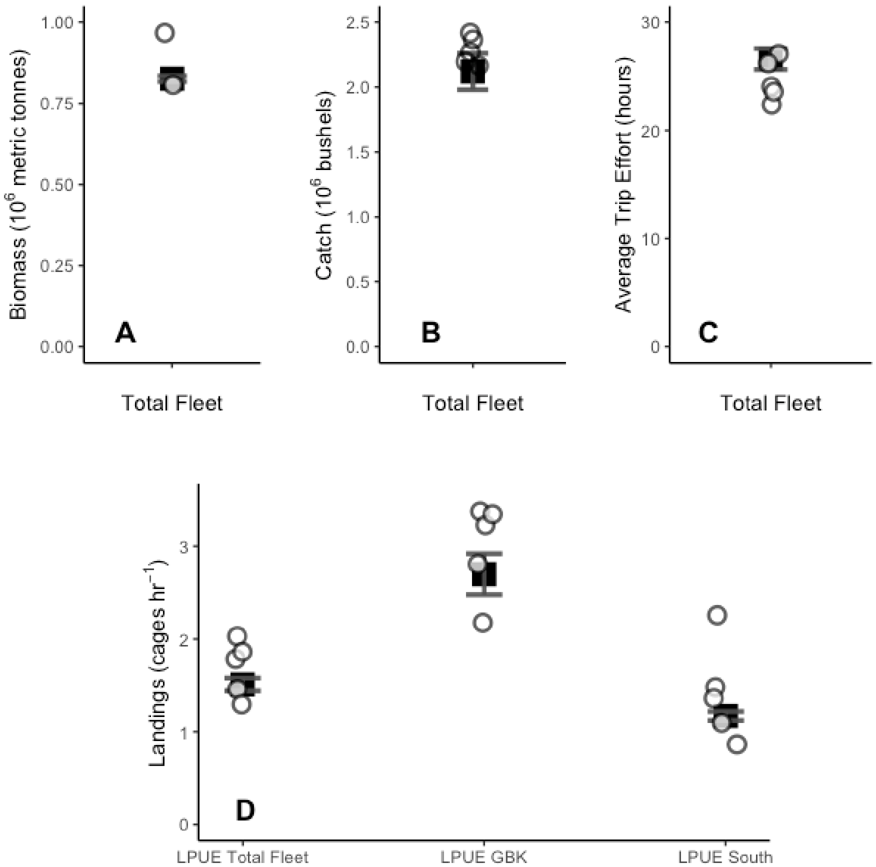


Figure 6: Simulated surfclam biomass, catch, and effort relative to survey observations. Average Atlantic surfclam A: biomass, and B: catch for the total fishing fleet; C: number of hours fishing per trip across the total fleet; D: landings per unit effort (LPUE) for the total fleet (left), only vessels fishing on Georges Banks (center, GBK), and the rest of the fleet (right, south) calculated from the fishing simulation (filled black squares). Corresponding observed values from the 2015 to 2019 annual stock surveys are shown (open black circles). Only two survey-based estimates for biomass were made between 2015 and 2019 (A). Standard deviations for the simulated averages are shown.

Simulated annual catch in millions of metric tonnes was slightly lower than the catch reported for 2015 to 2019 (Figure 6B; p=0.005, W=30). However, two of five observed catch values were within the standard deviation of model variability and the NRMSE is 0.09. The spatial pattern of simulated catch, in bushels per TMS, relative to the observed fishery (Figure 7) showed that the footprint of the simulated fishing fleet was similar to the actual fishery. In particular, the regions of enhanced catch (hotspots) were similar in the simulated and observed spatial distributions (Figure 7).

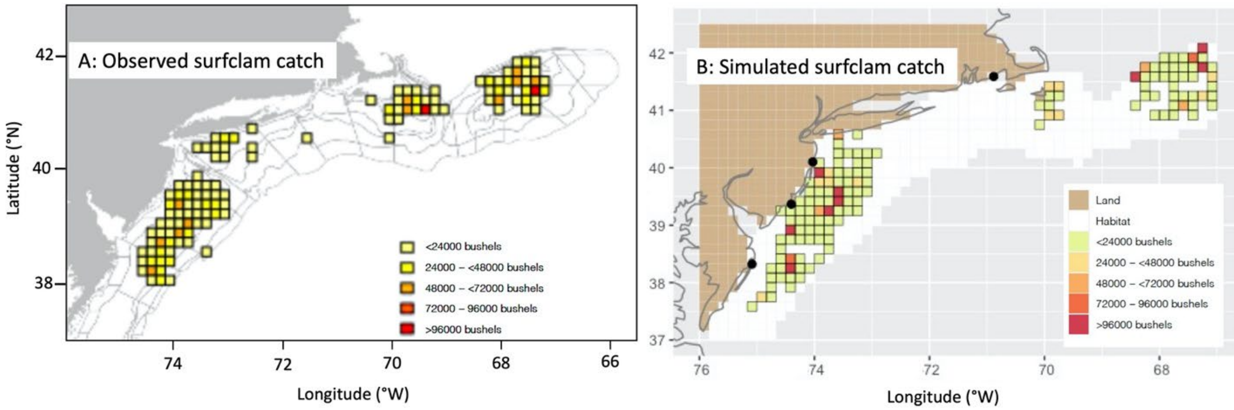


Figure 7: Simulated spatial pattern of catch relative to survey observations.
Spatial pattern of Atlantic average surfclam catch in bushels in each TMS per year obtained from the A) 2016 to 2019 stock assessment surveys and B) reference fishing simulation.

Simulated annual average number of fishing hours per trip was slightly higher than hours fishing per trip reported as part of the stock assessment (Figure 6C; p=0.02, W=203), yet has a low NRMSE of 0.10. There was considerable overlap in hours at sea per trip between simulated and trip times reported in GARFO (2021) (Figure 8A) as well as good predictive accuracy of the simulation at the individual vessel level, as shown by a median (across vessels) NRMSE value of 0.20 (Figure 9).

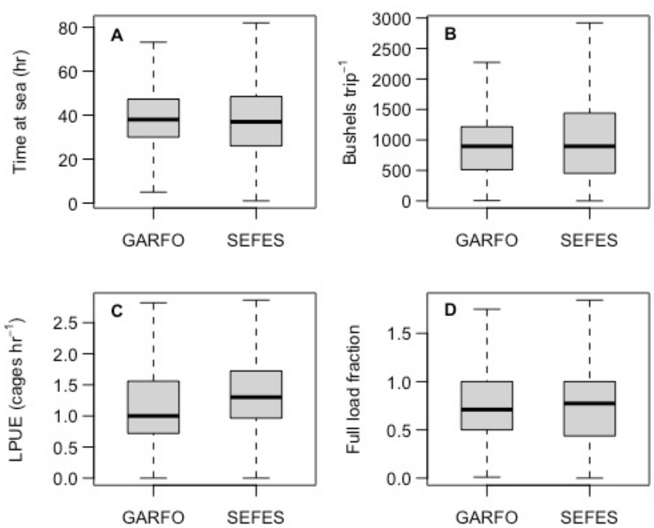


Figure 8: Comparison between observed and simulated catch and effort.
Comparison between observed (Greater Atlantic Fisheries Office, GARFO) and simulated average (A) dock-to-dock *Time at sea (in hours)* for fishing trips, (B) catch in *Bushels per trip*, (C) landings per unit effort, *LPUE (in cages per hour)*, and (D) *Full load fraction* of the fishing vessel for each trip. The observed values were obtained from GARFO (2021) trip data reports. Full-load fraction may exceed 1 as Atlantic surfclam fishing vessels occasionally have a large last haul and land more than the vessel cage capacity.

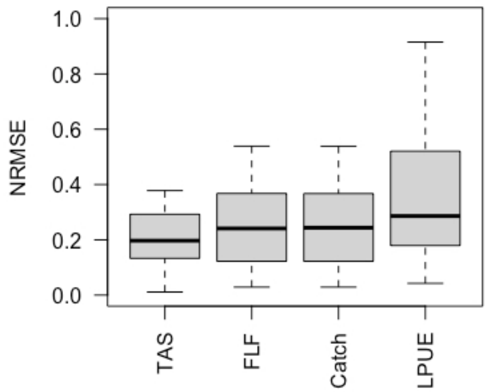


Figure 9: Model catch and effort skill.
Normalized root mean squared error (NRMSE) for annual average time-at-sea (TAS), full load fraction (FLF), catch, and LPUE per trip calculated for each simulated vessel (n=33).

Simulated and observed spatial patterns of fishing effort (hours fished) per TMS were similar (Figure 10). The simulated pattern placed more effort in some TMS compared to the observed pattern in the fishery, such as the Georges Bank region. Likewise, fishing effort showed a slightly greater spread over a larger area in the fishery compared to the simulated effort (Figure 10).

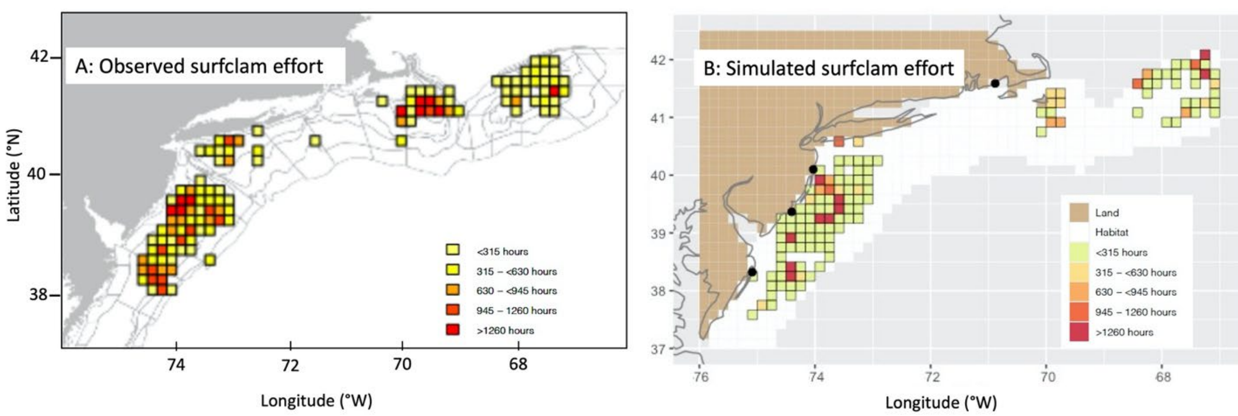


Figure 10: Simulated spatial pattern of fishing effort relative to survey observations.
Spatial pattern of average Atlantic surfclam fishing effort in hours fished in each TMS per year obtained from the A) 2016 to 2019 stock assessment surveys and B) the fishing simulation.

The simulated and observed catch, as bushels per trip, exhibited a similar, though broader, distribution compared to reported catch for fishing trips (GARFO, 2021; Figure 8B) and individual vessel behavior was well represented (median NRMSE = 0.24; Figure 9). The simulated and observed LPUE were also similar (Figure 6C) for the entire fleet (p=0.22, W=83; NRMSE = 0.20), the vessels only fishing in the south (p=0.37, W=94; NRMSE = 0.37), and the vessels fishing on Georges Bank (p=0.07, W=64; NRMSE = 0.18). Trip level LPUE values from the simulation were slightly higher on average but exhibited a range similar to reported values from fishing trips (Figure 8C). Individual vessel simulated LPUE was lower than reported values as indicated by a higher NRMSE (median NRMSE = 0.29; Figure 9), likely because LPUE depends both on simulated catch and effort. The fraction of a full load for a simulated fishing trip matched that calculated from reported fishing trip loads (GARFO, 2021; Figure 8D) and individual vessel predictive accuracy for trip loads was strong (median NRMSE = 0.24; Figure 9).

4.3 Validation Summary

Implementation of a *SEFES* as a reference simulation allowed investigation of the scale, variability, and change in spatial patterns of Atlantic surfclam stock biomass that resulted from the external factors imposed by catch, fishing effort, and behavior of fishing vessel captains. Stakeholder participation in agent-based modeling approaches helps ensure their use and value in management decision making (Matthews et al., 2007). Our modeling approach engaged experts from the fishery and from the management sector early in model conception, development, and reference simulation validation. These quantitative and qualitative analyses showed that this reference simulation has sufficient skill to represent the dynamics of Atlantic surfclam fishery. As such, this reference simulation can serve as the basis for subsequent studies designed to examine the response of the Atlantic surfclam fishery to displacement of fishing and survey effort due to offshore wind energy areas. These studies will be discussed in Chapters 5, 6, 7, and 8.

5 Cumulative Economic Impacts

The Atlantic surfclam fishing sector is highly consolidated and vertically integrated, with processing plants owning or controlling nearly all harvest quota and vessels operating in the fleet (Northern Economics, 2019). A large portion of processed product is supplied to a small number of national and multinational food service and soup companies. This market structure, in addition to persistent competition from imports, leaves processors little ability to control prices (Mitchell et al., 2011; Northern Economics, 2019). Small shifts in profitability caused by changes in vessel operations, harvest, and landings could therefore be consequential at the port or industry level. As industrialization of the ocean expands, there is a growing recognition that quantification and mitigation of adverse socioeconomic impacts is necessary to achieve sustainable and inclusive blue economic growth (Bennett et al., 2019; Haggett et al., 2020). Understanding the impacts of fishery exclusion and fishing effort displacement from development of offshore wind energy is critical to the sustainability of the Atlantic surfclam fishing industry.

The objective of simulations presented in this chapter is to quantify the potential economic impacts resulting from exclusion and spatial displacement of the Atlantic surfclam fishery arising under different offshore wind energy development scenarios. The analysis uses the *SEFES* reference simulation presented and validated in Chapter 4 as a base case from which to evaluate the effect of placement of offshore wind energy areas on the overall economic conditions of the Atlantic surfclam fishery.

5.1 Cumulative Impacts Simulations

The development of offshore wind energy in the MAB is expected to impact the Atlantic surfclam fishing industry, with potential effects including shifts in the number of trips taken, fishing locations, and transit routes. Economic impacts associated with exclusion and spatial displacement of the fishing fleet were assessed using a series of simulation scenarios that imposed restrictions on fishing and vessel transiting within existing wind energy lease areas as well as areas of anticipated future development (Table 5). Areas of potential future development were previously identified by the Bureau of Ocean Energy Management (BOEM) as suitable areas that may be considered for future leasing (BOEM, 2020a). The reference simulation is a scenario with no wind energy development, and therefore no restrictions on fishing or transit activity (StautsQuo, Table 5), provided a baseline for assessing the effects of restricted fishing and transit within existing leases (Cum1F, Cum1FT Table 5) and existing together with future lease areas (Cum2F, Cum2FT, Table 5). For simulations with imposed fishing behavior restrictions related to wind energy development, a TMS model grid cell was considered within a wind energy lease area if the polygons defining the lease area or potential future development area, including a 2-NM (~3.7 km) buffer, overlapped with 50% or more of a model grid cell (Figure 11, orange shaded cells). Scenarios that included potential future wind energy development (Cum2F, Cum2FT) increased the spatial footprint of offshore wind energy leases in the model by ~106%, effectively doubling the area with imposed behavioral restrictions.

Table 5: Cumulative impacts simulation scenarios.

Scenario	Wind Energy Development	Fishery Behavioral Restrictions
StatusQuo	None / status quo (reference simulation)	None
Cum1F	Existing lease areas*	No fishing
Cum1FT	Existing lease areas*	No fishing nor transit
Cum2F	Existing lease areas + future development**	No fishing
Cum2FT	Existing lease areas + future development**	No fishing nor transit

*Existing leases for cumulative simulations include OCS-A 0490, OCS-A0519, OCS-A 0482, OCS-A 0532, OCS-A 0498, OCS-A 0499, OCS-A 0549, OCS-A 0512, OCS-A 0506, OCS-A 0486, OCS-A 0517, OCS-A 0487, OCS-A 0500, OCS-A 0501, OCS-A 0534, OCS-A 0520 OCS-A 0521, OCS-A 0522.
**Future development areas for cumulative simulations include New York Bight Call Areas encompassing "Fairways North," "Fairways South," "Hudson North," and "Hudson South" (the Call Areas).

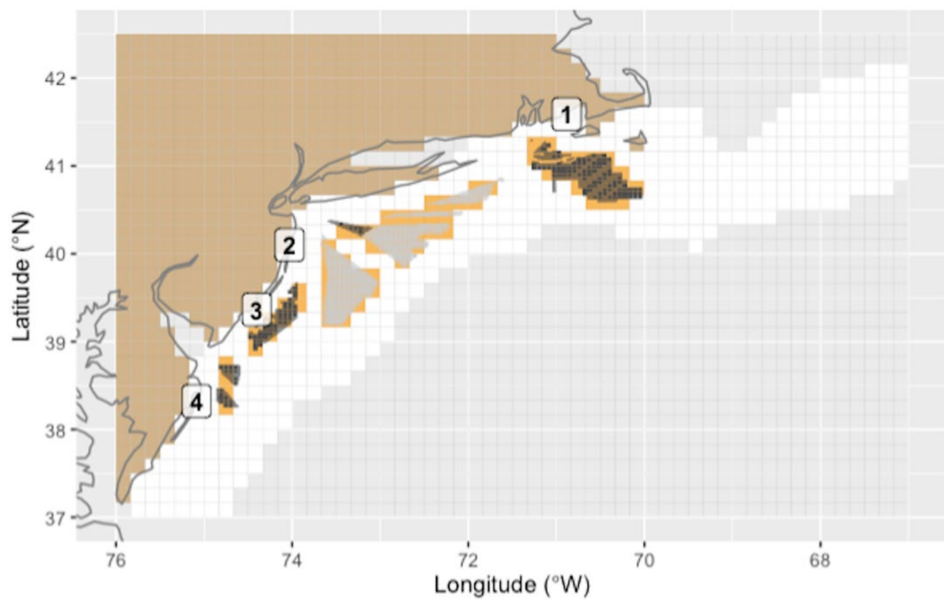


Figure 11: *SEFES* model domain with offshore wind areas overlaid.
Map of the Mid-Atlantic Bight showing existing offshore wind energy leases (dark grey) and potential future development areas (light grey). Model grid cells considered land (tan), those within the biological domain (white), and those in which fishing vessel behavioral restrictions were imposed in wind energy areas (orange shading under wind area polygons) are indicated. Locations of landing ports for Atlantic surfclam fishing vessels are indicated as: 1-New Bedford, MA; 2-Point Pleasant, NJ; 3-Atlantic City, NJ; and 4-Ocean City, MD.

5.1.1 Simulation Implementation

Five simulation scenarios were used to assess economic conditions of the Atlantic surfclam fishery with and without constraints imposed by the placement of wind energy areas (Table 5, pg. 28). Each scenario consisted of a set of 200 simulations. Each simulation included 33 vessels in the Atlantic surfclam fishing fleet with each vessel having a randomly assigned captain type based on one of 12 configurations. Captain types varied in searching behavior and how expectations of catch rates in different fishing locations were formed (see Chapters 3 and 4 for further description). Each simulation was run for 300 years, with no fishing during the first 100 years to allow the Atlantic surfclam population dynamics to stabilize. Fishing was enabled in the second 100 years of the simulation but without any wind energy-related behavioral restrictions to allow the Atlantic surfclam population to come into equilibrium with the current level of fishing mortality. The fishery behavioral restrictions associated with the presence of offshore wind energy areas were imposed in the last 100 years of a simulation. The simulation without wind energy areas (reference simulation, Chapter 4) continued without behavioral restrictions during the last 100 years. The number of trips, total time in hours spent steaming and fishing, and catch in cages and kilograms by week for each vessel during the last 50 years of a simulation (years 251 to 300) were used to assess economic impacts of wind energy scenarios on the Atlantic surfclam fishery. In the last 50 years of the simulations, the Atlantic surfclam population biomass was adjusted to constant fishing pressure and the associated random variability introduced by weather restrictions, captain fishing location choices, and recruitment variability, and therefore provided stable realizations of annual fishing activity. The use of 50 years of simulation data was not intended to provide impact projections extending 50 years into the future following construction of offshore wind energy areas, which would exceed the planned life of current turbine technology. Rather, a 50-year simulation window was chosen to provide a large set of annual impact estimates best interpreted as short- to medium-term effects (e.g., occurring one to five years following wind energy area construction).

Each set of simulations within a particular scenario yielded 17,160,000 weekly fishing vessel-level observations, which were aggregated to 330,000 annual vessel-level observations and 10,000 annual fleet-level observations. The total number of fishing trips, average time at sea per trip, average time fishing per trip, and average landings per unit effort (cages per hour fishing) were used to assess changes in fishing activity corresponding to changes in behavioral restrictions across the scenarios. Annual measures of fishing fleet revenues and costs and processor revenues were used to measure aggregate economic impacts. The Atlantic surfclam industry is thought to operate under modest profit margins; as an example, the fleet operates with low to negative profitability (Table 4, pg. 18) and annual quota is often left unfished because of market constraints. Small shifts in operating costs could reduce economic viability; therefore, economic impacts were further explored by analyzing average fleet total costs (USD cage^{-1}), average fleet fuel costs (USD cage^{-1}), and average processor transportation costs (USD cage^{-1}). Average fleet total costs were estimated by summing total costs for the simulated fishing fleet during one year and then dividing by the total number of Atlantic surfclam cages landed in that year. Average fleet fuel costs and average processor transportation costs were calculated similarly. Costs related to transporting product from landing sites to processing facilities were explored given the possibility of differential impacts on fishing behavior across ports coupled with differences in distances to processing infrastructure (Table 3, pg. 16). Assessment of the fishing simulations using a range of fishery independent, and fishery dependent data showed that the simulated biomass distributions and fishing fleet behavior accurately represented conditions in the present fishery (see Chapter 4). Analyses of the simulated economic outcomes focus on the sign and approximate magnitude of changes in fishing activity and economic measures in response to the development of offshore wind energy.

5.2 Results

5.2.1 Changes in Fishing Activity

Relative to the scenario with no fishing or transit restrictions (reference simulation, Chapter 4), simulations including wind energy areas reduced the total number of Atlantic surfclam fishing trips and increased average trip length (Table 6; see Table S1, pg. 56 for mean and standard deviation values). The number of fishing trips declined by 3.96% (Cum1F) to 14.57% (Cum2FT) when fishable and transitable areas were reduced. Average fishing trip length increased by 1.25% for vessels that transited, but could not fish, in existing wind energy areas (scenario Cum1F), and up to 12.68% when vessels could neither transit nor fish in existing and proposed lease areas (Dum1FT). Average fishing time per trip and landings per unit effort showed small decreases and increases, respectively, for simulations that considered restrictions imposed within existing leases (Cum1F, Cum1FT). The inclusion of proposed areas of future wind energy development (Cum2F, Cum2FT) led to small increases or unchanged average fishing times per trip and small reductions in landings per unit effort. Reductions in the number of trips and increases in average trip length were most prominent during the winter and fall (October through March) (see supplementary materials in Scheld et al., 2022 for more detail).

Table 6: Percent change* in annual fishing effort for cumulative impact simulation scenarios.

	Fishing Activity Simulation Scenario			
	No fishing in existing lease areas.	**No fishing or transit in existing lease areas.**	**No fishing in existing and proposed lease areas.**	**No fishing or transit in existing and proposed lease areas.**
Total Trips	-3.96	-7.42	-11.61	-14.57
Average Time at Sea	1.25	8.60	5.19	12.68
Average Time Fishing	-0.47	-2.47	1.51	-0.09
Average LPUE	1.63	3.46	-1.87	-0.29

* Changes were calculated relative to the reference simulation with no imposed restrictions on fishing or transit behavior (StatusQuo).

The imposition of restrictions on areas accessible to fishing and transit resulted in spatial shifts in simulated fishing effort, as measured by the change in total annual hours fished per model grid cell (Figure 12). Effort and catch displacement were primarily observed in the Mid-Atlantic region, where existing and proposed wind energy lease areas overlap with key Atlantic surfclam fishing grounds off New Jersey and New York (Figure 11, pg. 28). When prevented from fishing in existing wind energy leases, but still allowed to transit, fishing effort was displaced offshore of the existing wind energy lease areas off New Jersey (Figure 12a). Preventing transit as well as fishing access in existing wind energy lease areas concentrated fishing effort more heavily inshore (Figure 12b) and reduced overall catch (Figure S1b, pg. 60). The inclusion of proposed wind energy leases led to reductions in effort offshore of existing lease areas and increased fishing intensity in a small inshore region off New Jersey as well as further south (Figure 12c,d). Displacement of catch closely followed displacement of fishing effort (Figure S1, pg. 60). On Georges Bank, fishing effort and catch exhibited small shifts westward due to slightly longer steam times (Figures 12, S1, pg. 60). Aggregate effort and catch did not change substantially in this region across scenarios, however.

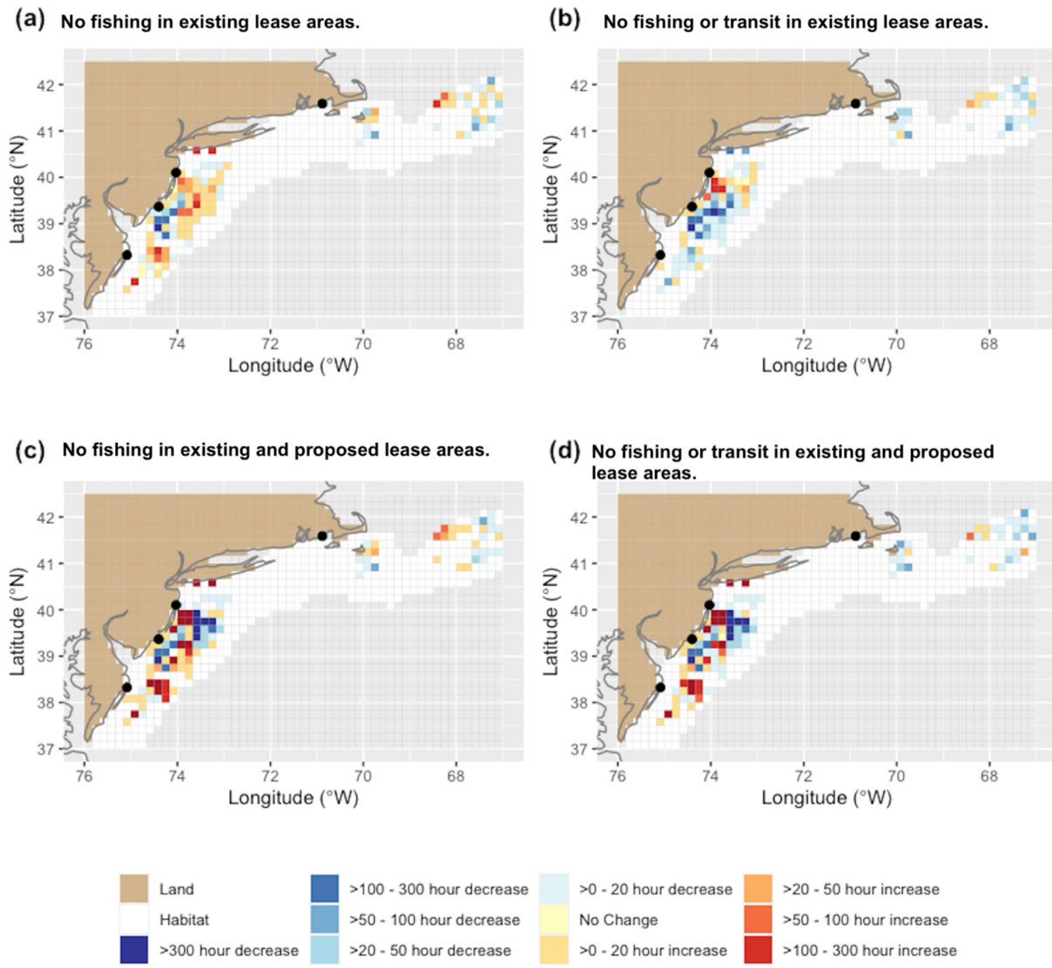


Figure 12: Simulated fishery effort displacement for cumulative impact simulation scenarios. Simulated Atlantic surfclam fishing effort displacement, indicated by the change in the average number of hours fished per model grid cell per year, for scenarios that allow (a) transit but no fishing in existing lease areas (Cum1F), (b) neither transit nor fishing in existing lease areas (Cum1FT), (c) transit but no fishing in existing and proposed lease areas (Cum2F), (d) neither transit nor fishing in existing and proposed lease areas (Cum2FT). Fishing effort displacement in each model grid cell was calculated for each simulation scenario relative to the average annual hours fished in that grid cell with no transit or fishing restrictions (StatusQuo, reference simulation). A decrease (increase) in average effort for a model grid cell under a particular scenario indicates behavioral restrictions led to less (more) time fishing in that area.

5.2.2 Economic Impacts

Changes in Atlantic surfclam fishing behavior produced several economic effects, with a contraction of total fishing fleet revenues of 2.84% (scenario Cum1F) to 14.85% (Cum2FT), consistent with reductions in trips taken by the fleet (Table 7; see Table S2, pg. 56 for mean and standard deviation values). The reduction in fishing effort translated into reductions in operational costs, with a reduction in simulated total fleet costs of 2.78% (Cum1F) to 10.70% (Cum2FT). Percentage reductions in Atlantic surfclam processor revenues mirrored reductions in fleet revenues, with minor differences due to seasonal variation in meat weight. In 2019 USD, simulated annual revenue reductions ranged from USD 0.93M (Cum1F) to

USD 4.84M (Cum2FT) for landed product and USD 3.27M (Cum1F) to USD 17.36M (Cum2FT) for processed product (Table S2, pg. 56). Average total costs and average fuel costs did not meaningfully change when Atlantic surfclam fishing was restricted in existing wind energy lease areas (Cum1F, Table 7). However, all other scenarios resulted in notable increases in average costs. In particular, scenarios restricting fishing vessel transit produced increases in average fuel costs of 5.55% (Cum1FT) and 9.92% (Cum2FT), which increased average total costs of production. Average transportation costs increased in all scenarios (Table 7) as proportionally more product was landed in New Bedford, MA, following greater changes in fishing activity for the southern portion of the fleet (Figure 12, Tables S3, S4, pg. 57). The market mix of wholesale products remained consistent across model scenarios, with ~22% of landings being processed as fresh, ~43% as frozen, and ~36% as canned products (Scheld et al., 2022).

Table 7: Percent change in economic outcomes for cumulative impact simulation scenarios.

Economic Outcomes	Simulation Scenario			
	No fishing in existing lease areas.	**No fishing or transit in existing lease areas.**	**No fishing in existing and proposed lease areas.**	**No fishing or transit in existing and proposed lease areas.**
Total Revenues (fleet)	-2.84	-6.53	-11.92	-14.85
Total Costs (fleet)	-2.78	-4.38	-9.37	-10.70
Total Revenues (processors)	-2.88	-6.62	-12.30	-15.31
Average Total Costs (fleet)	0.07	2.34	2.92	4.93
Average Fuel Costs (fleet)	-0.06	5.55	4.93	9.92
Average Transportation Costs (processors)	0.76	1.25	3.26	4.09

*Changes were calculated relative to the reference simulation with no imposed restrictions on fishing or transit behavior (StatusQuo).

Port-specific Atlantic surfclam fishing activity and economic measures showed regional differences, with negative effects of offshore wind energy development largely concentrated in Atlantic City, NJ (Tables S3, S4, S5, S6, pg. 57, and Figure 13). For Atlantic surfclam fishing vessels with a homeport in Atlantic City, introducing fishing and transit restrictions in wind energy areas led to reductions in simulated fishing trips from 5.46% (Cum1F, Table S3, pg. 57) to 20.54% (Cum2FT) and increases in average time at sea from 0.77% (Cum1F) to 14.70% (Cum2FT). Additionally, scenarios including restrictions in areas of potential future wind energy development resulted in reductions in landings per unit effort for Atlantic City fishing vessels of 7.44% (Cum2F) and 6.44% (Cum2FT). Simulated revenues for the Atlantic City fishing fleet and associated processors decreased by ~5% (Cum1F) to over 25% (Cum2FT) (Table S5, pg. 58). Average total costs and average fuel costs for these vessels also increased across all scenarios. The simulated fleet with New Bedford, MA as its homeport was mostly unaffected by lease area restrictions, although simulations imposing restricted transit within the wind energy lease areas (Cum1FT, Cum2FT) showed increased time at sea and average fuel costs (Tables S4, S6, pg. 58).

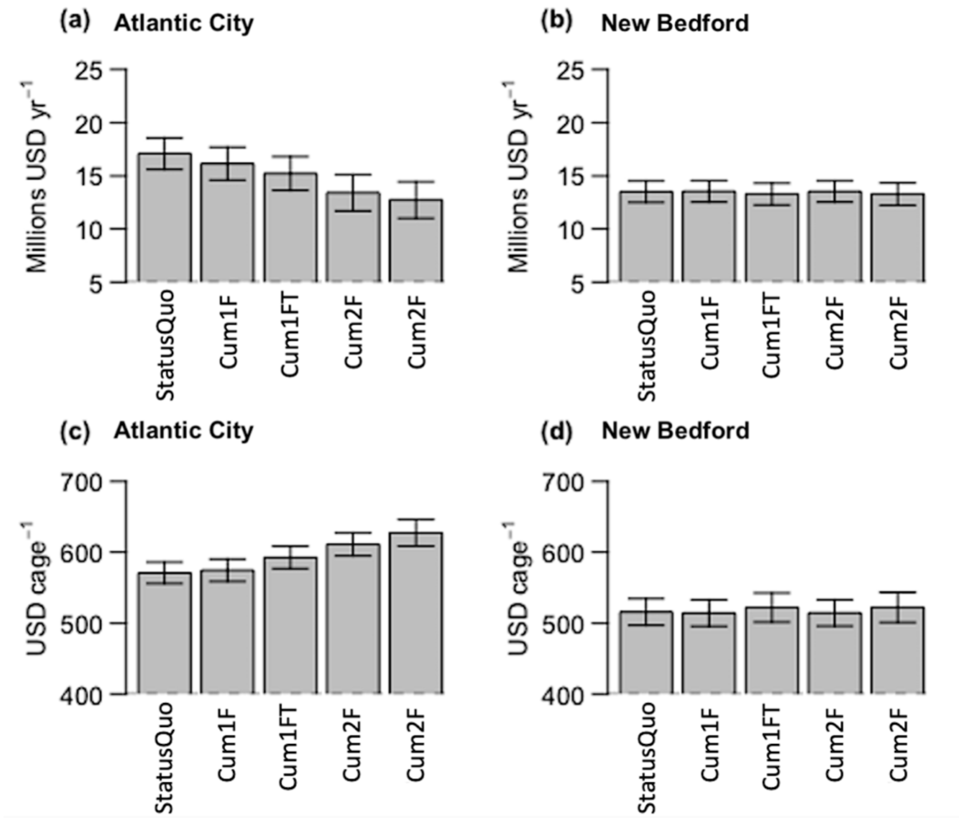


Figure 13: Simulated economic revenues and costs for cumulative wind energy scenarios.
Simulated economic metrics for each cumulative wind energy simulation scenario (see Table 5, pg. 28) for Atlantic surfclam fishing vessels landing in Atlantic City, NJ (left panels) and New Bedford, MA (right panels) showing, (a,b) total annual fleet revenues, and (c,d) average total costs. Values shown are means taken across 10,000 observations from the last 50 years of simulations for a particular scenario. Error bars indicate one standard deviation.

5.3 Cumulative Impacts Summary

Simulated restrictions on Atlantic surfclam vessel fishing and transit across all wind energy areas cumulatively increased fishing trip travel time and total time at sea, leading to reductions in the number of trips taken by the fleet and increased costs associated with displaced fishing effort. The current fleet fishes year-round, with boats frequently making one to two trips per week. Increases in travel time reduce the number of opportunities available to make fishing trips, leading to reduced landings revenues as well as increased average production costs. Total fishing costs also declined as a result of effort reductions, although these decreases were proportionately less than reductions in revenues. The combined effects of exclusion and resulting displacement of the Atlantic surfclam fishery from wind energy areas imply that profitability for the industry is likely to decrease as offshore wind energy resources are developed along the U.S. Northeast and Mid-Atlantic continental shelf.

While the magnitude of impacts differed across wind energy development scenarios, all showed reductions in fishing activity. The present Atlantic surfclam fleet directly employs ~130 individuals as crew (Table 2, pg. 16) and additionally supports many others working in processing plants and ancillary industries. In 2018, commercial fisheries in Mid-Atlantic states produced nearly USD 500 million in annual landings with total economic impacts of USD 1.8 billion that supported over 25,000 jobs (NMFS 2021). Using the National Renewable Energy Laboratory's Jobs and Economic Development Impact model for offshore wind, Tegen et al. (2015) estimated that operations and maintenance activities associated with a moderate level of offshore wind energy development in the Mid-Atlantic by 2030 would, similarly, support nearly USD 2 billion in annual economic activity and around 9,500 jobs, including 680 jobs in project development and onsite labor. Presently, many of the tradeoffs and interactions between the commercial fishing and offshore wind energy sectors are unclear, and much work remains to identify and promote potential synergies and co-benefits (Hooper et al. 2018; Schupp et al. 2019; Haggett et al. 2020; Methratta et al. 2020). Nevertheless, this analysis suggests that, cumulatively, the development of offshore wind energy may come with costs in terms of reductions in landings and fishing activity for certain commercially exploited species.

Seafood processing is an important source of employment and frequently a primary driver of profit generation for many coastal communities around the world (Anderson et al., 2015). The processing sector is rarely considered when evaluating impacts of policy or changes in fisheries management however, largely due to data limitations (Guldin and Anderson, 2018). For this analysis, the vertical integration of the Atlantic surfclam industry required consideration of the processing sector in assessing economic effects resulting from changes in fishing activity due to offshore wind energy development. Changes in processor revenues were found to closely follow changes in fishing fleet revenues due to consistent markups across product types. Additionally, the market mix of wholesale products remained relatively constant across simulation scenarios, despite heterogeneous impacts across regions and processors. Average transportation costs varied across wind energy development scenarios and among ports as travel distances for landed product were port-specific.

6 Regional Economic Impacts

The surfclam fishery operates in a spatially heterogeneous manner such that the distribution of vessels among ports is unequal and fishing effort varies spatially in response to the changing distribution of fishable patches of the stock (Kuykendall et al., 2017). For example, relatively few vessels fish out of Ocean City, MD, the southernmost port, and fishing effort tends to be highest at locations of abundant surfclam stock off New Jersey and west of the Great South Channel (Figure 10a, pg.25). These differences in localized fishing effort could create a situation in which the impacts from some areas of offshore wind energy development may have a disproportionate impact the fishery's performance than others. Simulations that isolate impacts regionally allow an exploration of how the spatial dynamics in the fishery interact with the locations of wind projects and provide a better understanding of the context of cumulative impacts across all of the projects.

The objective of simulations presented in this chapter is to independently examine the potential economic impacts resulting from exclusion and spatial displacement of the Atlantic surfclam fishery arising under different configurations of regional offshore wind energy development scenarios. The analysis uses the *SEFES* reference simulation presented and validated in Chapter 4 as a base case from which to evaluate the effect of placement of regional offshore wind energy areas on the overall economic conditions of the Atlantic surfclam fishery.

6.1 Regional Impacts Simulations

Sixteen simulations were used to regionally assess economic response of the Atlantic surfclam fishery when constraints are imposed on the fishery by the placement of wind energy areas (Table 8). Four regional wind energy overlays were used in these simulations, and for each regional overlay four levels of restrictions were imposed on the fishery: no fishing the leased TMSs, no fishing nor transit through leased wind energy TMSs, no fishing in leased and future leased wind energy TMSs, and no fishing nor transit through leased and future leased wind energy TMSs. Each of the 16 simulated scenarios followed the same strategy described for the cumulative impact simulations (section 5.1). The simulation without wind energy areas (reference simulation) described in Chapter 4 was used as the reference simulation against which the fishery performance from the regional simulations were compared.

Large surfclam (clams >120mm shell length) biomass, total annual catch, time at sea per trip, and time fishing per trip were used to assess changes in biology and fishing activity corresponding to changes in behavioral restrictions across the simulations. Annual measures of fishing fleet and processor revenues and costs were used to measure aggregate economic impacts. Assessment of the fishing simulations using a range of fishery-independent and fishery-dependent data showed that the simulated biomass distributions and fishing fleet behavior accurately represented conditions in the present fishery (see Chapter 4). Analyses of the simulated economic outcomes focus on the direction and relative magnitude of changes in fishing activity and economic measures in response to the offshore wind energy development.

Table 8: Regional economic impacts simulation scenarios.*

Region	Scenario	Wind Energy Development	Fishery Behavioral Restrictions
-	Status Quo	None / status quo (reference simulation)	None
A Delmarva	DMV1F	Existing lease areas (OCS-A 0490, OCS-A 0519, OCS-A 0482)	No fishing
“	DMV1FT	Existing lease areas (OCS-A 0490, OCS-A 0519, OCS-A 0482)	No fishing nor transit
“	DMV2F	Existing lease areas + future development	No fishing
“	DMV2FT	Existing lease areas + future development	No fishing nor transit
B New Jersey	NJ1F	Existing lease areas (OCS-A 0532, OCS-A 0498, OCS-A 0499, OCS-A 0549)	No fishing
“	NJ1FT	Existing lease areas OCS-A 0532, OCS-A 0498, OCS-A 0499, OCS-A 0549)	No fishing nor transit
“	NJ2F	Existing lease areas + future development (Call Area “Hudson South”)	No fishing
“	NJ2FT	Existing lease areas + future development (Call Area “Hudson South”)	No fishing nor transit
C Long Island	LI1F	Existing lease areas (OCS-A 0512)	No fishing
“	LI1FT	Existing lease areas (OCS-A 0512)	No fishing nor transit
“	LI2F	Existing lease areas + future development (Call Areas “Hudson North”, “Fairways South”, “Fairways North”)	No fishing
“	LI2FT	Existing lease areas + future development (Call Areas “Hudson North”, “Fairways South”, “Fairways North”)	No fishing nor transit
D Rhode Island Massachusetts	RIM1F	Existing lease areas (OCS-A 0506, OCS-A 0486, OCS-A 0517, OCS-A 0487, OCS-A 0500, OCS-A 0501, OCS-A 0534, OCS-A 0520 OCS-A 0521, OCS-A 0522)	No fishing
“	RIM1FT	Existing lease areas (OCS-A 0506, OCS-A 0486, OCS-A 0517, OCS-A 0487, OCS-A 0500, OCS-A 0501, OCS-A 0534, OCS-A 0520 OCS-A 0521, OCS-A 0522)	No fishing nor transit
“	RIM2F	Existing lease areas + future development	No fishing
“	RIM2FT	Existing lease areas + future development	No fishing nor transit

* Colors in the model domain map shown in Figure 14.

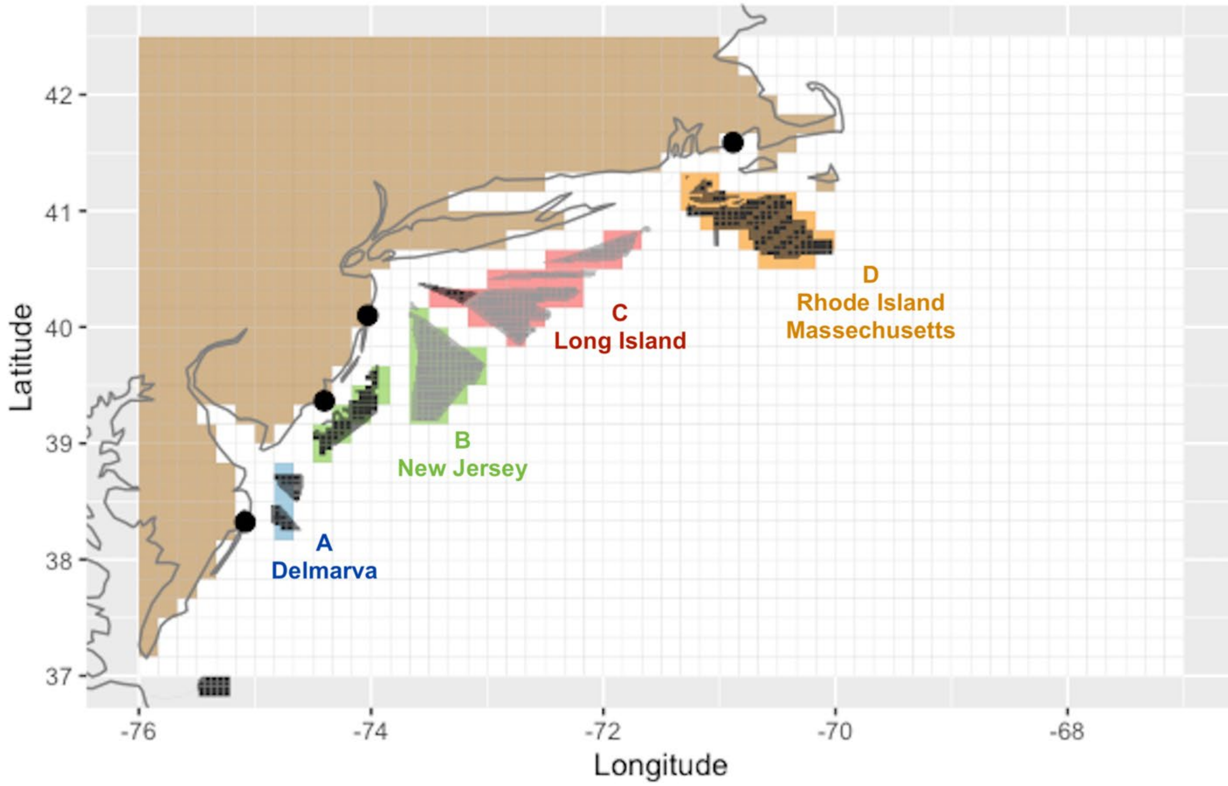


Figure 14: Regional wind lease overlays.
Model domain (grid represents the TMS in the model) with locations of ports (black dots) and each regional wind energy lease overlay identified with a different color Lease region A is in blue, lease region B is in green, lease region C is in red, and lease region D is in orange. The coastline is shown with a grey line, TMS shaded tan are defined as land, the footprint of the wind leases is overlaid in dark grey, and the future lease areas are shaded in light grey.

6.2 Results

6.2.1 Changes in Fishing Activity

Performance of the fleet tends to decline as restrictions due to wind energy areas increase, with catch declining and time spent at sea increasing as restrictions go from the smallest footprint to the largest and from only restricting fishing to restricting both fishing and transiting. For all simulated wind restrictions using regions A (Delmarva) or C (Long Island) the percent changes in fishing activity compared to the reference simulation are all relatively small, at less than 0.3% (Figure 15). The simulated wind restrictions using region D (Rhode Island/Massachusetts) are only evident in the no fishing nor transit cases with catch declining by 0.9% and time at sea increasing by 2.2% (Figure 15d). The greatest changes in fishing activity due to regional wind energy area restrictions are seen for region B (New Jersey) with catch declining from 3 to 13.5% and time at sea increasing from 0.6 to 7.7% (Figure 15b). The large surfclam biomass (clams >120mm shell length) is unchanged when wind energy area restrictions are simulated for regions A, C and D, yet large clam biomass increases slightly (0.2 to 1.2%) when region B restrictions are implemented (Figure 15).

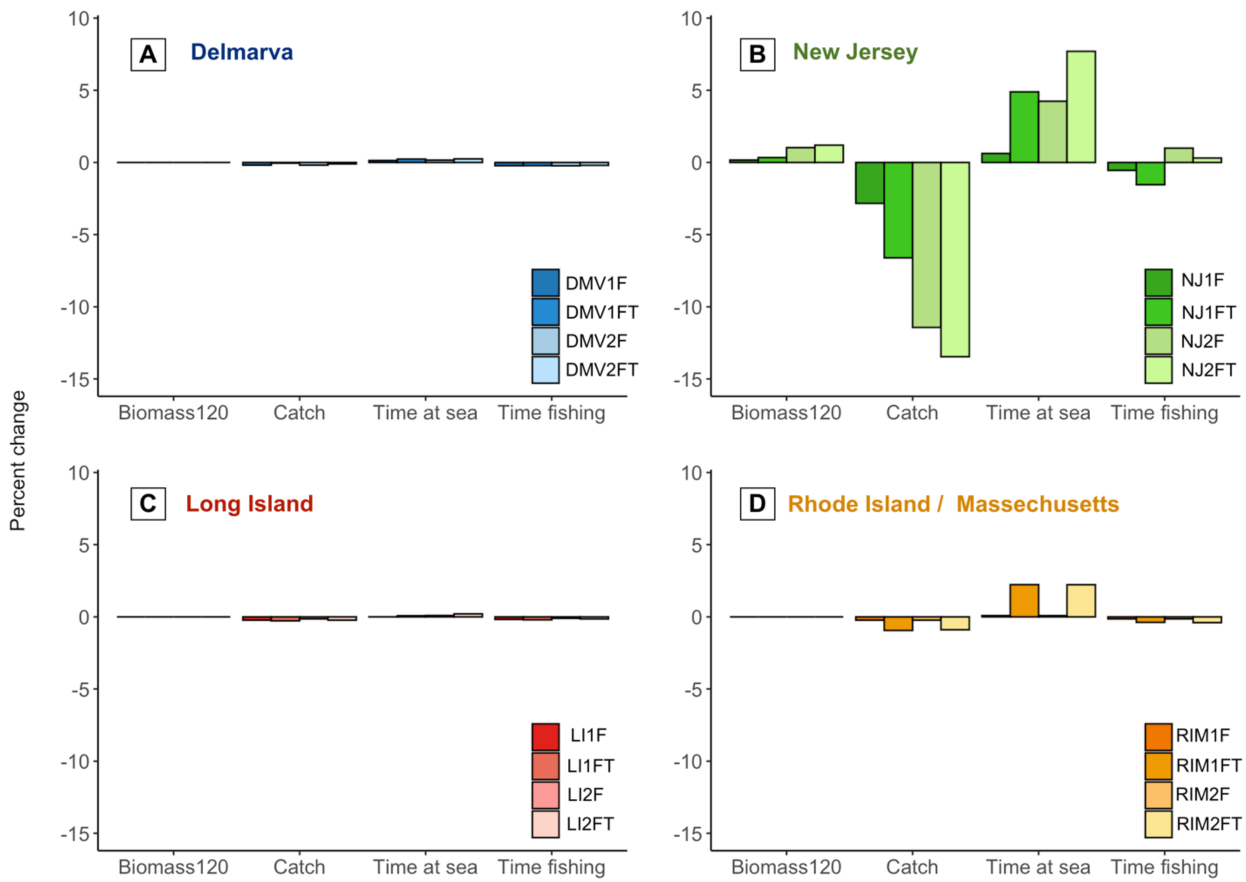


Figure 15: Change in biology and fishery behavior for regional wind area simulation scenarios. Percent change in large surfclam biomass (biomass of the clams >120mm shell length; Biomass120), annual average catch, annual time spent at sea, and annual time spent fishing for simulations with regional wind energy area restrictions compared to the Status Quo reference simulation. Panels A through D correspond to regional overlays A through D shown in Figure 14, and the color saturation corresponds to the simulation conditions shown in Table 8.

6.2.2 Economic Impacts

Economic performance of the fleet tends to decline as restrictions due to wind energy areas increase, with average costs increasing and revenues declining as restrictions go from the smallest footprint to the largest and from only restricting fishing to restricting both fishing and transiting. For all simulated wind energy area restrictions using regions A (DelMarVa) or C (Long Island) the percent changes in economics compared to the reference simulation are all relatively small, at less than 0.5% (most less than 0.05%, Figure 16). The simulated wind energy area restrictions using region D (Rhode Island/Massachusetts) are only evident in the no fishing nor transit cases with fleet revenues declining by 0.9%, profits declining by 2.5%, fuel costs increasing by 1.4%, and processor revenues declining by 0.8% (Figure 16d). The greatest changes in economics due to regional wind energy area restrictions are seen for region B (New Jersey) with fleet revenues declining by 3 to 14%, profits declining by 1 to 8%, average costs increasing up to 4%, fuel costs increasing by up to 8%, processor transport costs increasing by up to 4.5%, and processor revenues declining by 3 to 15% (Figure 16b).

When fleet revenues are examined at the port level for the two major ports in the fishery, Atlantic City and New Bedford, the economic losses and increased costs due to restrictions in region B (New Jersey) are mostly limited to vessels from Atlantic City and impacts of region D (Rhode Island/Massachusetts) are mostly limited to vessels from New Bedford (Figure 17). Similar to the pattern shown for total fleet economics, the economic impacts are greatest for region B (New Jersey) restrictions and impacts due to region D (Rhode Island/Massachusetts) are associated with the most restrictive scenario (no fishing nor transit). For each port of these two ports, the proportional economic change relative to the status quo is nearly double the fleet-wide impacts, highlighting their disproportionate vulnerability comparted to other ports.

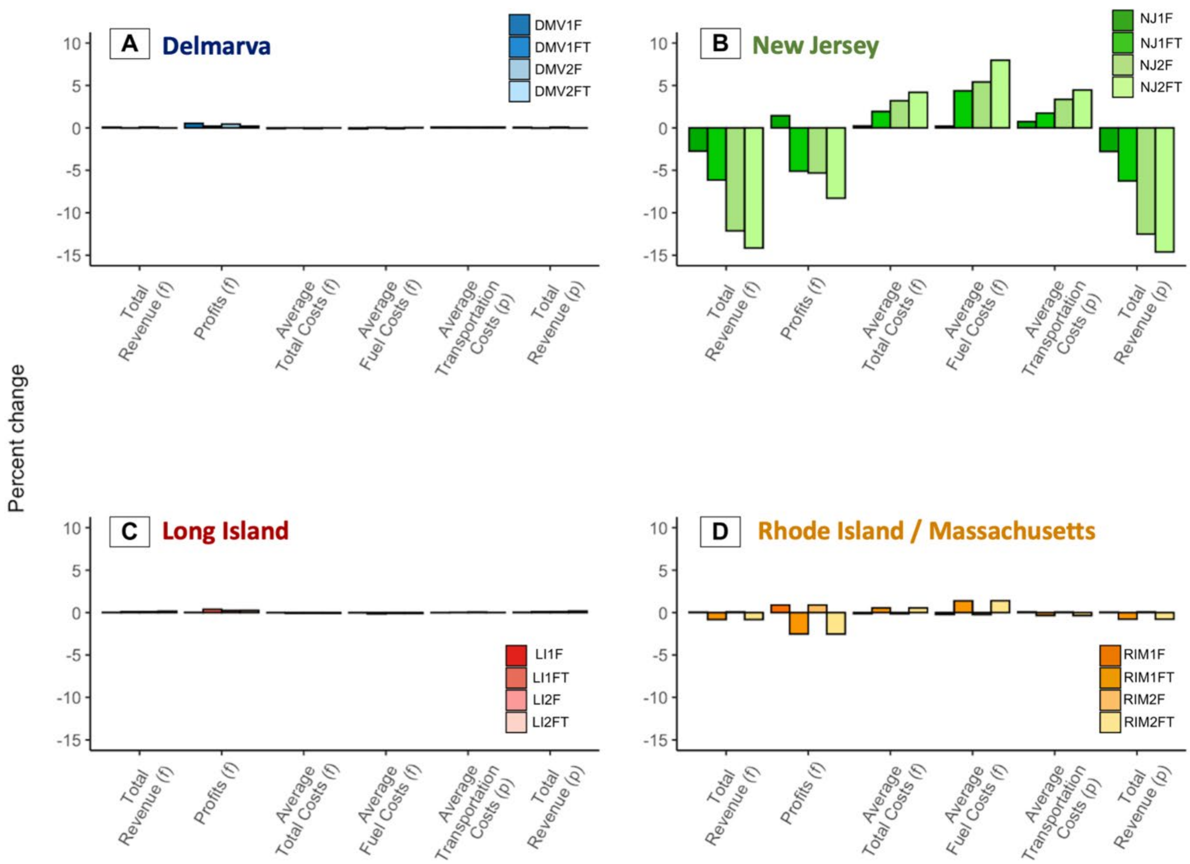


Figure 16: Relative change in fleet economics with regional wind area restrictions.
Percent change in total fleet revenue, fleet profits, total costs for the fleet averaged by cages of clams landed, fuel costs for the fleet averaged by cages landed, processor transportation costs averaged by the number of landed, and total annual revenue to the processor for simulations with regional wind energy area restrictions compared to the Status Quo reference simulation. Panels A through D correspond to regional overlays A through D shown in Figure 14 (pg. 37), and the color saturation corresponds to the simulation conditions (Table 8, pg. 36).

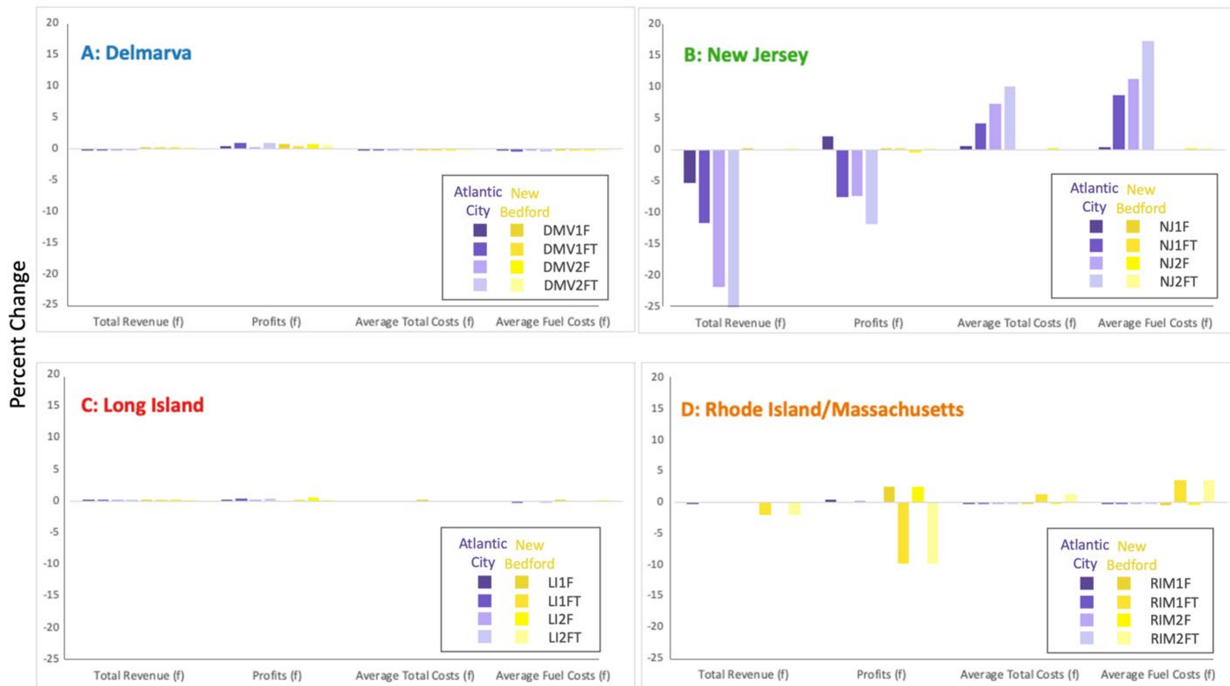


Figure 17: Relative change in fleet economics by port with regional wind area restrictions. Percent change in total fleet revenue, fleet profits, total costs for the fleet averaged by cages of clams landed, fuel costs for the fleet averaged by cages landed, broken down by major surfclam ports. Atlantic City shown in purple bars and New Bedford in yellow for simulations with regional wind area restrictions compared to the Status Quo reference. Panels A through D correspond to regional overlays A through D shown in Figure 14 (pg. 37), and the color saturation corresponds to the simulation conditions described in Table 8 (pg. 36).

6.3 Regional Impacts Summary

In these simulations, as restrictions on the fishery increase in severity or spatial footprint, vessels are forced to travel farther to reach fishing grounds and are displaced off preferred fishing grounds such that fishing effort is concentrated in smaller areas, ultimately driving costs of fishing up and revenues down. Although evident in all regional cases, this trend occurs disproportionately more when restrictions are imposed for wind energy leases in region B (New Jersey). Aside from the most restrictive case (no fishing nor transit) for region D (Rhode Island/Massachusetts) wind energy areas and all cases for region B (New Jersey) wind energy areas, the economic impacts to the fishery are relatively slight (<0.5%). However, restrictions imposed for region B (New Jersey) reach revenue losses up to 15% fleetwide, or 26% for the Atlantic City fleet alone.

The proportionally large losses associated with fishing and transit restrictions due to wind energy areas in region B (New Jersey) occur in the simulations because the contemporary surfclam fishery makes many of its annual trips to areas occupied by region B leases. In 2019, landings in the collective federal clam fisheries (surfclam and ocean quahog) from region B wind leases totaled $1.5 million USD (Benjamin et al., 2018; DePiper, 2014). This overlap of fishing activity and the region B lease areas therefore makes this area the most consequential in terms of interactions between the surfclam fishery and offshore wind. Surfclam fishing activity directly within other regions of wind energy areas are less than that occurring in region B, yet those other wind energy areas may act as navigation corridors that could lead to greater transit costs to the fishery if vessels navigate around these areas (as seen for region D simulations). The fishing effort that is displaced out of region B often end up displacing to other regional wind energy areas (Figure 12, pg. 31); therefore, it is important to consider cumulative impacts as well as examining smaller regional scenarios.

7 Surfclam Stock Survey Impacts

The Atlantic surfclam stock assessment is sensitive to survey constraints, including uncertainty imposed by limitations in the ability to survey the entire stock. The overlap of the federal Atlantic surfclam assessment survey strata and offshore wind energy areas may require modification to the survey design or make some stock areas inaccessible to the survey because of vessel handling limitations, safety requirements, and assessment protocols (Methratta et al., 2020). Changes to existing survey procedures or interruption of the long-term survey time series can increase uncertainty in biomass estimates used in setting fishery quotas, which in turn can lead to unintentional underharvest or overharvest, with consequent indirect impacts on the Atlantic surfclam stock and fishery. Additionally, increased uncertainty increases buffers used in setting annual catch limits which decreases annual quotas.

The objective of the simulations described in this Chapter is to evaluate the impact of excluding wind energy areas from the federal assessment survey on the Atlantic surfclam population biomass assessment. These scenarios simulate displacement of the survey out of these wind lease areas, and the concurrent displacement of fishing effort from the same areas, and thus reflect the collective changes to the assessment survey results and spatially dynamic changes to stock biology and fishing effort. Exclusion of survey operations from offshore wind areas can interrupt time-series and affects stock assessments by increasing uncertainty in estimates used in projecting fishery quotas.

7.1 Survey Simulations

Two simulations were used to assess the response of the Atlantic surfclam survey to an inability to survey within offshore wind energy areas. In these simulations, TMSs that include wind energy areas were excluded from the simulated annual assessment survey. Excluding these areas also reduced the area available for estimating the simulated Atlantic surfclam stock biomass. These simulations used a wind energy area overlay that included all existing leases (Cum1), and the existing wind areas plus the propsed future areas (Cum2). Two scenarios were simulated; one that excluded survey vessel operation and fishing in wind energy areas, the other excluded survey vessel operation and fishing in current and proposed future wind energy areas. Each simulated scenario followed the same strategy described for the cumulative impact simulations (section 5.1). The simulation without wind energy areas (reference simulation) described in Chapter 4 was used as the reference simulation against which the survey restriction simulations were compared.

Surfclam length data obtained from the simulated stock surveys was used to estimate wet weight (using eq. 1), which is used to calculate Atlantic surfclam stock biomass. Percent change in simulated fishable biomass, C_{Wn}, was calculated for simulations that included existing leases (Cum1) and existing and proposed wind energy lease areas (Cum2) relative to the no wind energy lease area scenario as:

$$C_{Wn} = \frac{\left(Biomass_{Wn} - Biomass_{ref}\right)}{Biomass_{ref}} \quad ,n = 1,2 \tag{16}$$

where $Biomass_{Wn}$ is the biomass from the simulations (n gives the simulation number) that included exclusion of the survey from wind energy lease areas and $Biomass_{ref}$ is the biomass from the reference simulation that included no restrictions on the survey.

The calculated percent change in Spawning Stock Biomass (SSB) for both simulations was then applied to the observed SSB from the most recent Atlantic surfclam stock assessment. Applying these percent changes to the observed SSB scales the observed SSB relative to lost survey opportunity due to exclusion from wind energy lease areas. The adjusted SSB (SSB_{AdjWn}), which represents the current spawning stock biomass adjusted for the simulated loss of biomass, was calculated as:

$$SSB_{AdjWn} = SSB_{Obs} - (|C_{Wn}| \times SSB_{Obs}) \quad , n = 1,2 \tag{17}$$

where SSB_{obs} is the observed spawning stock biomass obtained from the federal assessment survey, which is set at 1,222 thousand metric tons ('000mt); the SSB that was estimated in 2020 (NEFSC, 2022).

The spawning stock biomass at MSY for the simulations that excluded wind energy areas, SSB_{WnMSY} was then calculated as:

$$SSB_{Wn\,MSY} = \frac{SSB_{AdjWn}}{SSB_{Threshold}} \quad , n = 1,2 \tag{18}$$

where SSB_{AdjWn} is from equation (6) and $SSB_{Threshold}$ is set at 513 ('000mt) (NEFSC, 2022).

Total simulated catch was defined as the sum of simulated landings plus 12% to account for incidental fishing mortality (NEFSC, 2022). Simulated catch for each wind energy area scenario was estimated and converted from bushels to metric tons (Table 9).

Table 9: Atlantic surfclam catch conversion factors.

Unit	Equivalent
1 Cage	32 bushels
1 metric ton	130 bushels

The simulated rate of fishing-induced mortality for each wind energy lease area scenario, F_{Wn}, was calculated from the ratio of animals removed from the stock from fishing, $Catch_{Wn}$, to the total biomass, $Biomass_{Wn}$, as:

$$F_{Wn} = \frac{Catch_{Wn}}{Biomass_{Wn}}, \qquad n = 1,2 \tag{19}$$

The adjusted fishing mortality, F_{AdjWn}, was then estimated for each wind energy area simulation as:

$$F_{AdjWn} = F_{Obs} - \left(\left(\frac{F_{Wn} - F_{ref}}{F_{ref}}\right) \times F_{Obs}\right) \quad , n = 1,2 \tag{20}$$

where F_{obs} is the observed fishing mortality of 0.036 yr^{-1} obtained from NEFSC (2022), F_{Wn} is from equation 19, and F_{ref} is the fishing mortality obtained from the reference simulation that included no restrictions on the survey.

The fishing mortality that allows MSY, F_{WnMSY}, was calculated from the simulations that excluded the wind areas as:

$$F_{Wn\,MSY} = \frac{F_{AdjWn}}{F_{Threshold}} \quad ,n-1,2 \qquad (21)$$

where F_{AdjWn} is from equation 20 and $F_{Threshold}$ is set at 0.141 yr^{-1} (NEFSC, 2022).

7.2 Survey Results

7.2.1 Atlantic Surfclam Biomass

The mean fishable biomass of Atlantic surfclams estimated from the *SEFES* reference simulation (Chapter 4), with unrestricted access to the wind energy lease areas, was 0.585 million metric tonnes. Relative to this value, the percent change in total biomass from the simulations that excluded fishing from current and current and proposed wind energy areas increased by 0.34% and 1.20%, respectively (Figure 18). Exclusion of the survey from the wind energy areas also resulted in displacement of the simulated fishing effort to areas outside the leases sites, producing a decline in catch and an increase in fishable biomass.

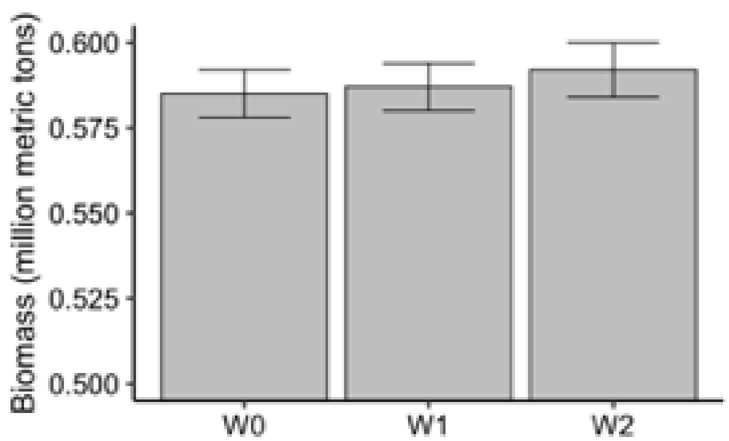


Figure 18: Total simulated Atlantic surfclam biomass with restricted fishing.
Total simulated surfclam biomass under conditions of unrestricted fishing (StatusQuo), conditions that excluded fishing from wind energy areas (Cum1) and conditions that excluded from wind energy areas and proposed future wind energy areas (Cum2). Values shown are means taken across 10,000 observations from the last 50 years of simulations for a particular scenario. Error bars indicate one standard deviation.

Exclusion of the simulated surveys from the current and current and proposed wind energy areas, resulted in decreases in simulated SSB of 3.5 and 17.3% respectively, relative to the reference simulation with unrestricted access. Adjusting the observed SSB of 1,222(‘000mt) (NEFSC, 2022) to reflect these decreases yielded a loss of 43.1 and 211.4 (‘000 mt) of SSB. The relative SSB was then calculated using the adjusted SSB, the ratio of the adjusted SSB to the reported $SSB_{Threshold}$ estimated in 2020 (NEFSC, 2022), which showed that exclusion of the survey from the current wind energy areas achieved 114.8% of the Atlantic surfclam biomass target (NEFSC, 2022) (Figure 19). Exclusion of the survey from current and proposed future wind energy areas resulted in a SSB biomass that was 1.6% below the SSB target (NEFSC, 2022) (Figure 19).

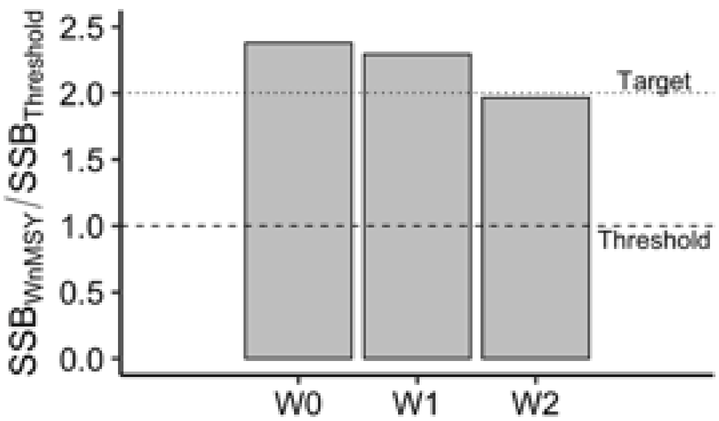


Figure 19: Relative spawning stock biomass of surfclam biomass with survey restrictions. Simulated relative spawning stock biomass (SSB_{WnMSY} /$SSB_{Threshold}$) of Atlantic surfclam biomass from the unrestricted survey (Chapter 4) (NEFSC, 2022), simulated spawning stock biomass for surveys that were excluded from wind energy areas (Cum1), and surveys excluded from wind energy areas and proposed future wind energy areas (Cum2).

7.2.2 Fishing mortality

The simulated Atlantic surfclam catch and biomass from the surveys decreased in response to restrictions on survey vessel operations in wind energy areas. Fishing mortality (catch/biomass) increased by 0.7 and 7.3% for the two wind energy area exclusion scenarios, respectively, relative to the reference simulation with unrestricted access. Adjusting the observed F (0.036 yr^{-1}) to reflect these increases resulted in an increase in this rate by 0.0002 and 0.003. Relative fishing mortality, calculated as the ratio of the adjusted F to the reported $F_{Threshold}$ estimated in 2020 (NEFSC, 2022), increased in both simulated scenarios remaining well below the overfishing threshold provide in NEFSC (2022). Consequently, neither simulated condition resulted in the occurrence of overfishing (Figure 20).

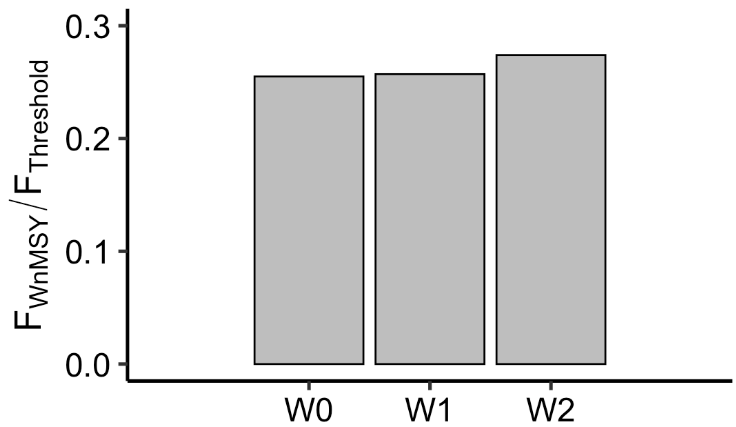


Figure 20: Relative Atlantic surfclam fishing mortality with survey restrictions.
Relative fishing mortality ($F_{WnMSY} / F_{Threshold}$) of the Atlantic surfclam fishery from the unrestricted survey (Chapter 4), simulated fishing mortality for wind energy areas (Cum1) and wind energy areas and proposed future wind energy areas (Cum2).

7.3 Survey Impacts Summary

Wind energy development plans in the United States will not automatically exclude other uses of wind energy areas by fishers or survey efforts, yet users such as commercial fisheries may be limited by other barriers (safety of navigation, lack of insurance, gear conflicts, etc.). It is anticipated that the federal assessment survey, which uses a commercial Atlantic surfclam fishing vessel, will experience displacement from wind energy areas once they are developed. Our simulations suggest that exclusion of the survey from wind energy areas will result in approximately 3.5% to 17.3% of the Atlantic surfclam SSB becoming inaccessible to the survey and effectively removed from the fishery. Additionally, perceived fishing mortality will increase, by 0.7 to 7.3%, because of the combination of reduction of observable stock biomass and changes in catch due to changes in fishing behavior. The decreased Atlantic surfclam biomass obtained from the survey and associated uncertainty in stock estimates have the potential to trigger use of a precautionary approach that will impose more restrictive management measures. It should be noted that BOEM and NMFS are working on plans to allow NMFS scientific surveys to adapt to and account for the presence of offshore wind facilities (Hare et al., 2022).

The simulated total Atlantic surfclam biomass increased nominally in the fishery and survey exclusion simulations because larger individual surfclams remained in wind energy areas. However, these simulations did not account for habitat loss due to other infrastructure, such as subsurface cables and scour protection (i.e., large boulders, gravel or cobble used to limit scour around turbine bases). Approximately 1,170 hectares of habitat could be lost across the U.S. Northeast Atlantic due to the added scour protection needed to protect wind turbine foundations (BOEM, 2020b; ICF, 2020). This loss of habitat would decrease overall Atlantic surfclam biomass within wind energy areas, making the simulated increase in overall biomass an overestimate of the actual changes that would result from offshore wind energy development. The realized changes in Atlantic surfclam biomass that result from the combination of lower fishing effort and alteration of habitat within wind energy areas is an important area of future study.

8 New York Bight Lease Areas

At the time of model development and initial simulations, the wind energy areas now delineated as the New York Bight lease areas had not been determined. Consequently, our previous simulations included a larger contiguous block that was identified as potential future wind energy areas to be considered for leasing (‘Call Areas’ used in simulations designated Cum2F and Cum2FT in Chapters 4, 5, and 6). Portions of the ‘Call Areas’ were removed from consideration as BOEM identified the ultimate lease blocks that would be included in the Final Sale Notice for the New York Bight lease areas. In the end, the Final Sale Notice included 8 wind energy leases that were 72% smaller in area than the original ‘Call Area’ (BOEM, 2022). Additionally, transit corridors that are 2.44 nautical miles wide were included in the layout of the New York Bight wind energy areas. The map shown in Figure 21 shows a comparison of the refined wind energy areas, the original Call Areas, and the transit lanes. Given this substantial change in lease area, new simulations were implemented that used the refined New York Bight wind energy areas and transit corridors.

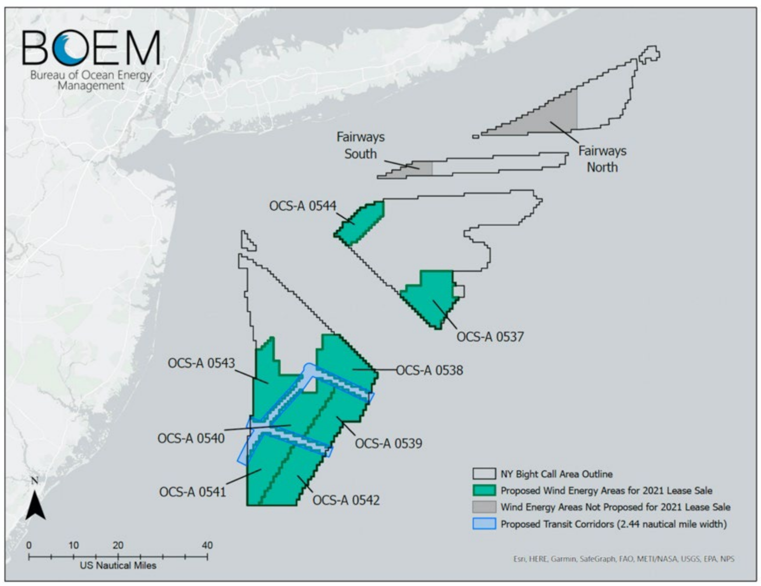


Figure 21: New York Bight Call Areas and final Lease Areas.
Map (from BOEM) showing the original outline of the Call Areas (black outline) used in simulations in Chapters 4, 5, 6, and 7, and final New York Bight lease areas (green fill) and transit corridors (blue paths).

8.1 New York Bight Simulations

Two simulations were used to assess the economic response of the Atlantic surfclam fishery when constraints are imposed on the fishery by the New York Bight wind energy areas. These simulations used a wind energy area overlay that included all existing wind energy areas, the 8 New York Bight leases, and transit corridors (Figures 21 & 22). As before, a TMS in the model domain was designated as part of a wind energy area if 50% or more of the area in that TMS overlaps with the wind energy area footprint (Figure 22). The overlay was imposed with two levels of restrictions on the fishery: no fishing the wind energy TMSs (NYF), no fishing and transit through wind energy TMSs restricted to the transit corridors (NYFT). In the no fishing and transit simulation (NYFT), vessels could transit through the NYB lease area, but could only do so by moving along the designated corridors (Figure 21). Each simulated scenario followed the same strategy described for the cumulative impact simulations (section 5.1). The simulation without wind energy areas (reference simulation) described in Chapter 4 was used as the reference simulation against which the fishery performance from the New York Bight simulations were compared.

Large surfclam (clams >120mm shell length) biomass, total annual catch, time at sea per trip, and time fishing per trip were used to assess changes in biology and fishing activity corresponding to changes in behavioral restrictions across the simulations. Annual measures of fishing fleet and processor revenues and costs were used to measure aggregate economic impacts. Assessment of the fishing simulations using a range of fishery-independent and fishery-dependent data showed that the simulated biomass distributions and fishing fleet behavior accurately represented conditions in the present fishery (see Chapter 4). Analyses of the simulated economic outcomes focus on the direction and relative magnitude of changes in fishing activity and economic measures in response to the development of offshore wind energy.

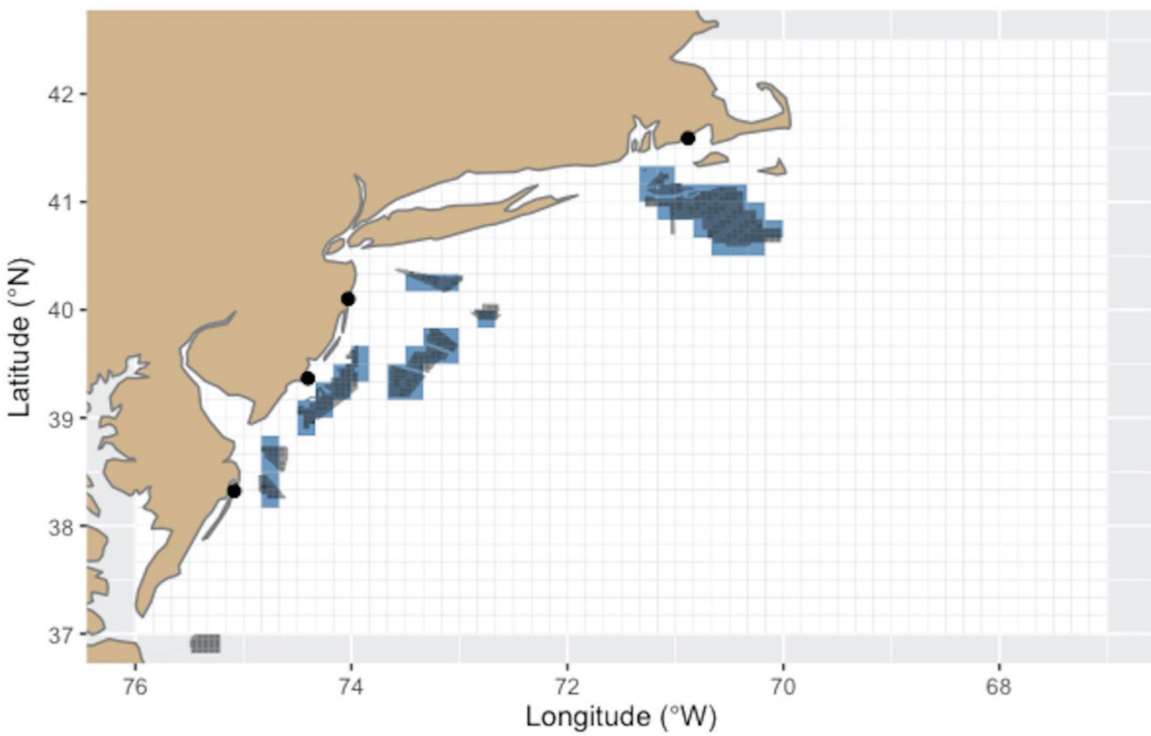


Figure 22: *SEFES* model domain with offshore wind areas, including New York Bight leases.
Map of the model domain showing existing offshore wind energy areas (dark grey). Model TMS within the biological domain (white), and those in which fishing vessel behavioral restrictions were imposed in wind energy areas (blue shading under wind area polygons) are indicated. Locations of landing ports for Atlantic surfclam fishing vessels are indicated with black circles.

8.2 Results

Time spent at sea across the fleet increases as restrictions go from only restricting fishing to restricting both fishing and transiting despite including transit corridors (Figure 23a). However, reduction of the wind energy footprint to the New York Bight areas and allowing transit corridors increased the time spent at sea by less than 5%, while the simulations using the full Call Areas increased time at sea to over 12%

in the most restrictive case (see Table 6, pg. 30). Overall catch declines by 9%, regardless of the level of restrictions (Figure 23a), a lower loss of catch than the ~15% decline in catch in the simulations using the full Call Areas (Chapter 5; Cum2F and Cum2FT). Time spent fishing slightly increased fleetwide when only fishing was restricted across all of the wind energy areas but declined by 2.2% when fishing and transit (with corridor allowances) were restricted. Biomass of the largest clams is relatively unchanged in these simulations (Figure 23a).

Total revenue at both the fleet and processor levels declines by about 9% for both restricted fishing and restricted fishing and transiting cases (Figure 23b), a smaller loss in revenue than 12 to 15% losses that resulted from simulations using the full Call Areas (Chapter 5; Cum2F and Cum2FT). Average total costs to fish fleetwide increase 2 to 4%, with fuel costs increasing 4 to 9% (Figure 23b), cost increases that are comparable to increases that resulted from simulations using the full Call Areas (Chapter 5; Cum2F and Cum2FT).

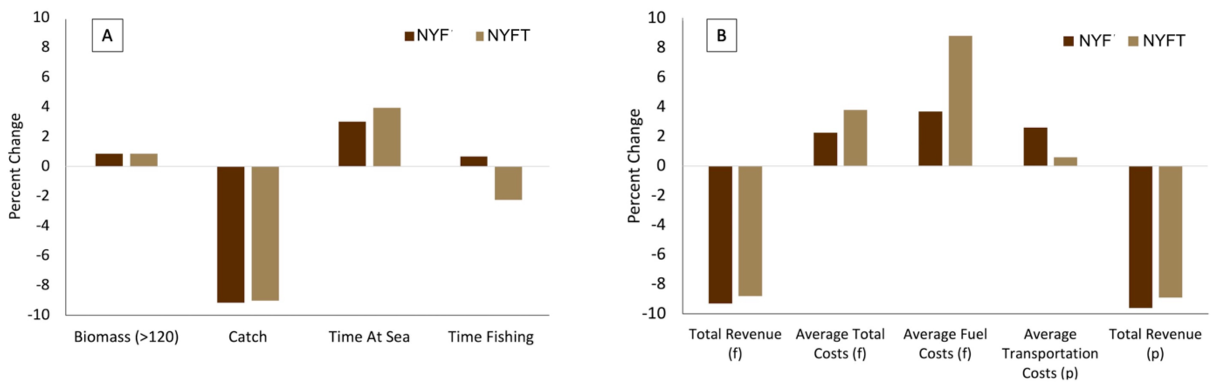


Figure 23: Change in biology, fishery behavior and economics for New York Bight simulations. Percent change in large surfclam (clams >120mm shell length) biomass, annual average catch, annual time spent at sea, and annual time spent fishing for simulations New York Bight wind area restrictions compared to the StatusQuo reference simulation described in Chapter 4 (Panel A, left). Percent change in total fleet revenue, total costs for the fleet averaged by cages of clams landed, fuel costs for the fleet averaged by cages landed, processor transportation costs averaged by the number of landed, and total annual revenue to the processor for simulations New York Bight wind energy area restrictions compared to the StatusQuo reference simulation described in Chapter 4. Color saturation corresponds to the simulation conditions of only fishing restricted (dark color) and fishing restriction and transit only through specified corridors (lighter color).

Number of annual trips decreases, and time spent at sea increases for each of the Atlantic City and New Bedford fleets as restrictions go from only restricting fishing to restricting both fishing and transiting (Figure 24). However, the percent change in trips and time at sea for the Atlantic City fleet is an order of magnitude greater than the changes for the New Bedford fleet. Fleet and processor revenue for the Atlantic City fleet decline by 15% to 17% compared to the StatusQuo reference simulation (Figure 24), a lower decline than the 21% to 25% decline in revenue that resulted from the simulations using the full Call Areas (Chapter 5; Cum2F and Cum2FT).

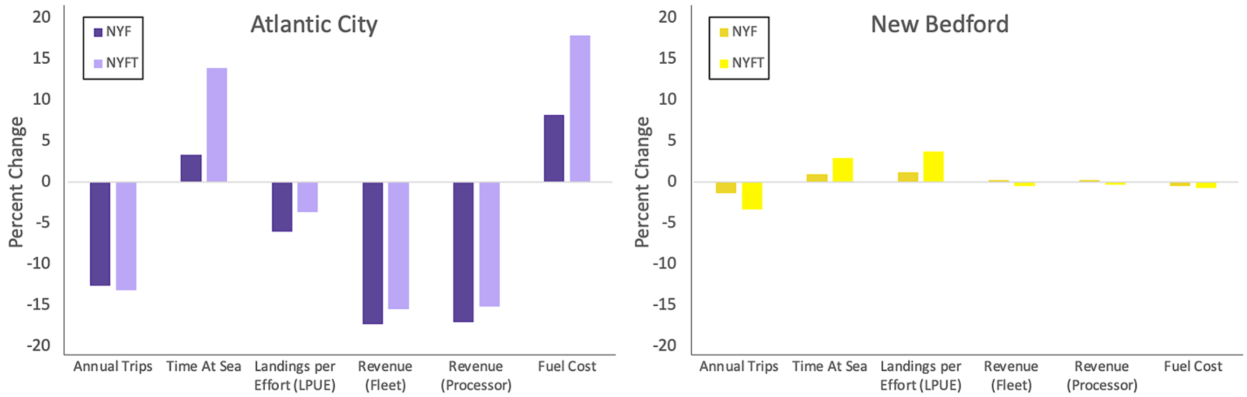


Figure 24: Port-specific change in fishing for New York Bight simulations.
Percent change in annual average trips, annual time spent at sea, landings per unit effort, fleet and processor revenue, and fuel costs for simulations New York Bight wind area restrictions compared to the StatusQuo reference simulation described in Chapter 4. Left panel (purple bars) shows percent changes for the Atlantic City fleet, and the right panel (yellow bars) shows percent changes for the New Bedford fleet. Color saturation corresponds to the simulation conditions of only fishing restricted (dark color, NYF) and fishing restriction and transit only through specified corridors (lighter color, NYFT).

8.3 New York Bight Simulations Summary

As in previous simulations, in these New York Bight simulations, as restrictions on the fishery increase, vessels are forced to travel farther to reach fishing grounds and are displaced off preferred fishing grounds such that fishing effort is concentrated in smaller areas, ultimately driving costs of fishing up and revenues down. The reduction in wind energy area footprint from the Call Areas to the New York Bight wind energy leases (a reduction of 72% of the original footprint) decreases the behavioral and economic impacts on the fishery when restrictions due to wind energy areas are imposed, although cost increases remain comparable. By reducing the wind energy footprint to the New York Bight leases, losses in catch and revenue due to fishery displacement are reduced from ~15% to ~9% fleetwide, and revenues specific to the fleet in Atlantic city are reduced from ~24% to ~16%. Increases in costs of fishing are maintained for the smaller New York Bight lease footprint, yet revenue losses are reduced, highlighting the importance of opportunity to maintain catches over a larger area of ocean bottom in mitigating impacts of wind energy areas on this fishery. Allowing transit through corridors among the New York Bight lease areas does not eliminate increases in time at sea and costs of fishing due to transit restrictions, but corridors tend to slightly reduce the degree to which transit restrictions impact the fishery.

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Appendix A: Supplementary Materials

A.1 Supplementary Tables

Table S1: Fishing activity metrics across cumulative scenarios.

Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Average time at sea and average time fishing are shown as hours per trip. Average LPUE is shown as cages per hour fished. Standard deviations are presented beneath means in italics.

	StatusQuo	No fishing in existing lease areas.	No fishing or transit in existing lease areas.	No fishing in existing and proposed lease areas.	No fishing or transit in existing and proposed lease areas.
Total Trips	1870.207	1796.129	1731.482	1653.101	1597.804
	88.942	*92.724*	*96.705*	*105.000*	*103.603*
Average Time at Sea	41.631	42.152	45.211	43.791	46.908
	1.314	*1.376*	*1.244*	*1.421*	*1.360*
Average Time Fishing	25.124	25.005	24.504	25.504	25.100
	0.859	*0.869*	*0.892*	*1.023*	*0.983*
Average LPUE	1.512	1.537	1.565	1.484	1.508
	0.057	*0.058*	*0.059*	*0.056*	*0.060*

Table S2: Economic metrics across cumulative scenarios.

Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Total revenues and costs are in millions of 2019 USD. Average costs are 2019 USD per landed cage. Standard deviations are presented beneath means in italics.

	StatusQuo	No fishing in existing lease areas.	No fishing or transit in existing lease areas.	No fishing in existing and proposed lease areas.	No fishing or transit in existing and proposed lease areas.
Total Revenues (fleet)	32.595	31.670	30.465	28.711	27.755
	2.092	*2.219*	*2.376*	*2.407*	*2.428*

Total Costs (fleet)	38.752	37.674	37.055	35.119	34.604
	1.920	*2.070*	*2.299*	*2.415*	*2.438*
Total Revenues (processors)	113.406	110.140	105.900	99.460	96.045
	7.568	*8.042*	*8.618*	*8.642*	*8.651*
Average Total Costs (fleet)	546.137	546.522	558.918	562.102	573.077
	11.199	*11.463*	*12.579*	*12.299*	*14.055*
Average Fuel Costs (fleet)	182.617	182.503	192.755	191.622	200.727
	6.898	*6.948*	*7.590*	*7.361*	*8.568*
Average Transportation Costs (processors)	19.440	19.587	19.683	20.075	20.236
	0.513	*0.550*	*0.621*	*0.726*	*0.809*

Table S3: Fishing activity metrics across cumulative scenarios for landings in Atlantic City, NJ.

Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Average time at sea and average time fishing are shown as hours per trip. Average LPUE is shown as cages per hour fished. Standard deviations are presented beneath means in italics.

	StatusQuo	**No fishing in existing lease areas.**	**No fishing or transit in existing lease areas.**	**No fishing in existing and proposed lease areas.**	**No fishing or transit in existing and proposed lease areas.**
Total Trips	1235.772	1168.335	1109.335	1030.911	981.899
	67.934	*68.269*	*68.786*	*78.026*	*78.585*
Average Time at Sea	34.264	34.528	37.598	36.235	39.300
	1.488	*1.596*	*1.617*	*1.785*	*1.808*
Average Time Fishing	24.889	24.634	24.093	25.225	24.845
	1.046	*1.076*	*1.115*	*1.395*	*1.340*
Average LPUE	1.210	1.221	1.239	1.120	1.132
	0.051	*0.052*	*0.053*	*0.049*	*0.050*

Table S4: Fishing activity metrics across cumulative scenarios for landings in New Bedford, MA.

Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Average time at sea and average time fishing are shown as hours per trip. Average LPUE is shown as cages per hour fished. Standard deviations are presented beneath means in italics.

	StatusQuo	**No fishing in existing lease areas.**	**No fishing or transit in existing lease areas.**	**No fishing in existing and proposed lease areas.**	**No fishing or transit in existing and propose d lease areas.**
Total Trips	482.374	476.796	471.790	476.832	471.038
	34.233	*34.426*	*33.806*	*34.002*	*33.803*
Average Time at Sea	62.914	63.521	66.337	63.468	66.567
	3.998	*4.195*	*4.122*	*4.124*	*4.228*
Average Time Fishing	26.410	26.507	26.145	26.542	26.122
	1.392	*1.417*	*1.423*	*1.400*	*1.418*
Average LPUE	2.318	2.342	2.354	2.337	2.359
	0.165	*0.171*	*0.167*	*0.163*	*0.171*

Table S5: Economic metrics across cumulative scenarios for landings in Atlantic City, NJ.

Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Total revenues and costs are in millions of 2019 USD. Average costs are 2019 USD per landed cage. Standard deviations are presented beneath means in italics.

	Status Quo	**No fishing in existing lease areas.**	**No fishing or transit in existing lease areas.**	**No fishing in existing and proposed lease areas.**	**No fishing or transit in existing and proposed lease areas.**
Total Revenues (fleet)	17.088	16.146	15.221	13.406	12.720
	1.487	*1.548*	*1.597*	*1.715*	*1.724*
Total Costs (fleet)	21.217	20.171	19.617	17.812	17.345
	1.488	*1.592*	*1.784*	*1.990*	*2.017*
Total Revenues (processors)	61.799	58.461	55.182	48.596	46.104
	5.421	*5.640*	*5.853*	*6.217*	*6.201*

Average Total Costs (fleet)	570.710	574.368	592.480	611.177	627.542
	14.965	*15.806*	*15.805*	*16.608*	*18.974*
Average Fuel Costs (fleet)	186.458	187.182	201.275	206.594	218.962
	9.433	*9.994*	*10.575*	*10.284*	*11.180*
Average Transportation Costs (processors)	13.506	13.440	13.398	13.181	13.291
	0.515	*0.581*	*0.633*	*0.761*	*0.951*

Table S6: Economic metrics across cumulative scenarios for landings in New Bedford, MA.

Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Total revenues and costs are in millions of 2019 USD. Average costs are 2019 USD per landed cage. Standard deviations are presented beneath means in italics.

	Status Quo	**No fishing in existing lease areas.**	**No fishing or transit in existing lease areas.**	**No fishing in existing and proposed lease areas.**	**No fishing or transit in existing and proposed lease areas.**
Total Revenues (fleet)	13.504	13.530	13.277	13.522	13.275
	1.009	*1.005*	*1.032*	*0.999*	*1.057*
Total Costs (fleet)	15.132	15.119	15.053	15.115	15.055
	0.631	*0.630*	*0.638*	*0.627*	*0.650*
Total Revenues (processors)	44.302	44.408	43.545	44.365	43.525
	3.480	*3.486*	*3.566*	*3.451*	*3.648*
Average Total Costs (fleet)	515.500	514.068	521.733	514.229	522.019
	18.806	*18.682*	*20.429*	*18.558*	*21.203*
Average Fuel Costs (fleet)	181.790	181.110	187.616	181.226	187.936
	14.569	*14.569*	*15.827*	*14.481*	*16.462*
Average Transportation Costs (processors)	26.866	26.852	26.835	26.845	26.852
	0.542	*0.543*	*0.537*	*0.531*	*0.540*

A.2 Supplementary Figures

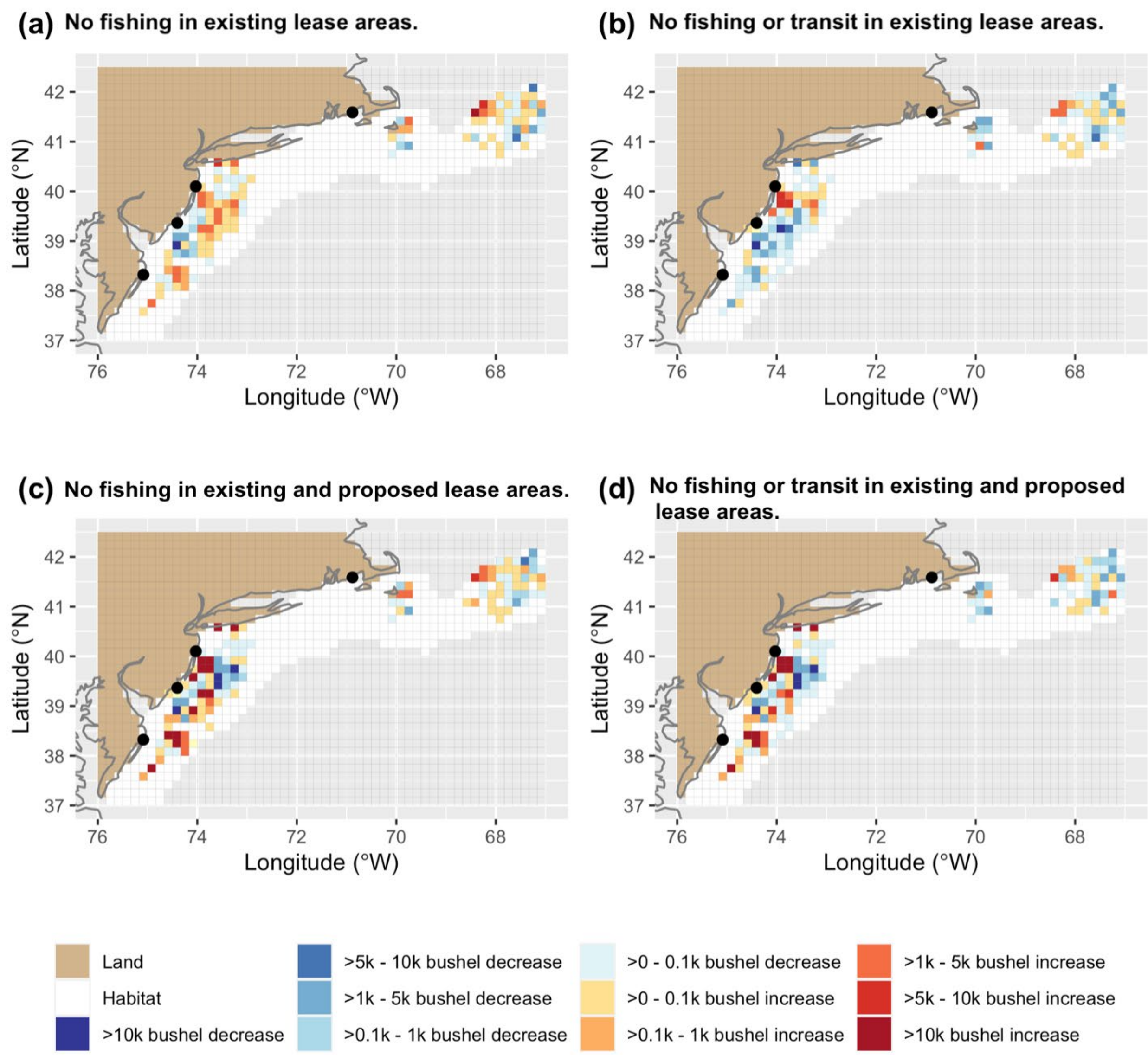

Figure S1: Atlantic surfclam catch displacement due to wind energy area restrictions.
Simulated Atlantic surfclam catch displacement, indicated by the change in the average number of bushels caught per model grid cell per year, for scenarios that allow (a) transit but no fishing in existing lease areas (Cum1F), (b) neither transit nor fishing in existing lease areas (Cum1FT), (c) transit but not fishing in existing and proposed lease areas (Cum2F), (d) neither transit nor fishing in existing and proposed lease areas (Cum2FT). Catch displacement in each model grid cell was calculated for each simulation scenario relative to the average annual catch in that grid cell with no transit or fishing restrictions (StatusQuo). A decrease (increase) in average catch for a model grid cell under a particular scenario indicates behavioral restrictions led to less (more) catch in that are

Department of the Interior (DOI)

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Bureau of Ocean Energy Management (BOEM)

The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program

The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM's Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).