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Atlantic Surfclam Fishing and Windfarms in the Future Ocean

Interactive Effects of Wind Farms and Future Ocean Conditions on the Surfclam Fishery

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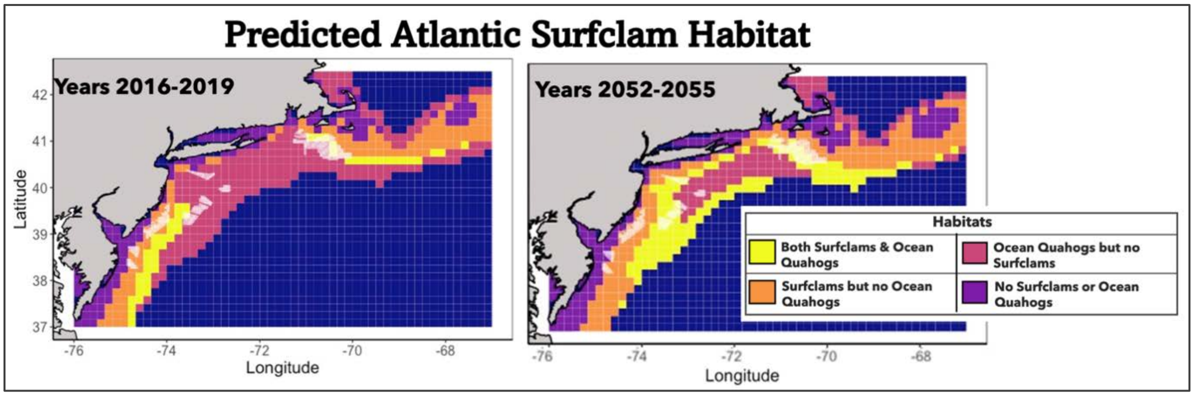
Executive Summary

In this project, we forecast and evaluate responses of the Atlantic surfclam fishery to the combined challenges of climate change and overlap of fishing grounds and offshore wind projects. Our approach estimates future Atlantic surfclam ranges on a 50-year time horizon, based on ocean climate forecasts to more holistically estimate impacts of offshore wind energy development along the U.S. east coast on the Atlantic surfclam fishery for both present-day and potential future conditions.



Our main findings from this forecast modeling approach are:

- By 2050, Atlantic surfclam habitat increases by 36% and habitat supporting both ocean quahog and Atlantic surfclam increases 152%
- Increased habitat generates 58% more Atlantic surfclam biomass by the 2050's
  - Southern-most and northern-most regions show little change in biomass, whereas New Jersey and Long Island regions show large increases in biomass (130% and 417% respectively).
- Increased biomass supports a forecasted 20% increase in fishery catch by the 2050's
  - The greatest increases in catch are seen in New Jersey (35%), Long Island (167%), and Southern New England (19%).
- Imposing restrictions related to offshore wind area locations reduces catch between 8-13% in least restrictive case and between 16-18% in the most restrictive case.
  - Catch declined the most for the New Jersey region (-37% for the least restrictive and -42% for the most restrictive case).
  - Catch increased for the Long Island region (15% for the least restrictive and 20% for the most restrictive case).
- The increased catch due to biomass expansion is shown to support a 2050 scenario similar to unrestricted catch in contemporary conditions with imposed offshore wind restrictions.
- Regional dynamics in changes in catch are driven by shifting fishing effort to areas outside of wind lease areas off the coast of New Jersey and Rhode Island, into areas off Long Island where Atlantic surfclam biomass is predicted to expand.

Introduction

The Atlantic surfclam (*Spisula solidissima)* fishery is an important commercial fishery in the U.S. Northeast region. Annual landings of approximately 22,400 tonnes (50 million lbs) generate over USD 30 million. The fishery operates on high volume and low margin, making it highly vulnerable to small shifts in economic efficiency. The fishery is conducted in the Middle Atlantic Bight (MAB), a marine region where seasonal temperature extremes are undergoing long-term changes at rates faster than other continental shelves (Saba et al., 2016; Friedland et al., 2022; Amaya et al., 2023). The MAB region is characterized by a strong seasonal thermocline that overlies and stabilizes a cold pool of water on the bottom (Horwitz et al., 2023). This cold bottom water sustains boreal fauna over a range that extends farther south than would be anticipated just by latitude (Borsetti et al., 2018; Narváez et al., 2015).

The Atlantic surfclam is particularly sensitive to changes in thermocline stability and bottom water temperatures. The warming of MAB bottom waters is considered to be the cause of the shift in southern and inshore extent of fishable abundances to the north and offshore in recent decades (Munroe et al., 2016; Narváez et al., 2015). However, commercial fishing resumed in 2021 in southern stock regions previously reported as lost habitat. Studies of the size, age, and condition of Atlantic surfclams from these southern areas showed that multiple successful recruitment events have occurred in the south during recent years and that Atlantic surfclams are growing normally relative to the central portion of the stock (Wisner et al., 2023). Nonetheless, recent estimates by Timbs et al. (2019) indicate that the Atlantic surfclam stock has shifted 20 km offshore and 30-40 km north off Delmarva and New Jersey over the last few decades. These shifts, should they continue at these rates, could have important interactive effects on the impacts of wind farm installations on the economics of the fishery.

In this project, we forecast and evaluate responses of the Atlantic surfclam fishery to currently leased and proposed future wind farms over the approximately 30- to 50-year life span of these wind energy installations with consideration for forecasted climactic changes. Our approach is premised on a strategy that estimated future range shift dynamics on a 50-year time horizon, based on ocean climate forecasts. Our projections of environmental conditions in the MAB shelf are obtained from an oceanographic circulation model that evolves with monthly forcing (Drenkard et al., 2021), in response to forcing fields based on a subset of the latest Intergovernmental Panel on Climate Change (IPCC) projections that encompass a range of outcomes in order to constrain model uncertainty. The simulated future oceanographic conditions provide time series of ocean temperature that is then used to calculate spatially-resolved biological probabilities for habitat suitability and survival across the current and projected range occupied by the Atlantic surfclam.

Forecast Atlantic surfclam distributions are then used in a **S**patially explicit, **E**cological, agent-based **F**isheries and **E**conomics **S**imulator: *SEFES.* The agent-based fishery model was previously developed to simulate the Atlantic surfclam fishery in the MAB (Munroe et al., 2022). The model integrates spatial dynamics in stock biology, fishery captain and fleet behavior, federal management decisions, fishery economics, and port structure and was used to investigate changes in Atlantic surfclam fishing behavior and economics due to wind energy areas (Scheld et al., 2022). Model processes and structure are outlined in Munroe et al. (2022) and Scheld et al, (2022), and will not be recapitulated herein. The model is unique in its integration of emergent properties such as fishing effort displacement, decreases in fishing efficiency, and increased fishing costs that result from interactions with wind farm areas. Previous studies with the model have addressed these interactions using present-day conditions for the fishery and the stock (Munroe et al., 2022; Scheld et al., 2022; Borsetti et al., 2023; Stromp et al., 2023a). However, throughout the lifetime of the planned wind energy installations (3 to 5 decades), projected changes in ocean conditions may lead to changes in stock distribution that could alter these interactions. Thus, anticipation of the cumulative impacts of wind energy development along the U.S. east coast on the Atlantic surfclam fishery requires consideration of both present-day and potential future conditions.

Future Ocean Forecasts

In order to study climate change impacts on marine ecosystems we carried out downscaled physical-biological projections. The goal was to downscale global Earth System models and provide a small ensemble of high-resolution ocean-ecosystem projections. Our multi-scale approach resulted in simulations useful for the work on climate change impacts on the surfclam at high spatial resolutions necessary to resolve the relevant dynamics and geography.

The large-scale climate change signals were obtained using global climate and earth system models from the Climate Model Intercomparison Project version 6 (CMIP 6) archive. For this project, we used simulations that utilized the Representative Concentration Pathway (RCP) 8.5 scenarios, which project strong greenhouse gasses loading into the atmosphere through the 21st century. We diagnosed the large-scale changes over the 21st century simulated by the models and used them to provide the climate change forcing to the regional, high-resolution, Regional Ocean Modeling System (ROMS) model boundary conditions. These included the fluxes of heat, moisture and momentum at the ocean surface and the advection of heat, salt and biogeochemical fluxes along the ocean boundaries.

Given the biases in present day global climate/earth system models and their relatively coarse resolution (~80-220 km) using their output directly to drive higher resolution ocean models may result in an unrealistic representation of the ocean climate and its response to an increase in greenhouse gasses. In addition, if a single or small subsample of climate model simulations are used to drive a regional ocean model, a significant part of the changes, including long-term trends, may be due to natural variability as opposed to the response to greenhouse gasses (Deser et al. 2012a&b, 2014). We address these issues and produce high-resolution, bias-corrected ensemble averaged physical-biogeochemical projections for the Northeast U.S. by combining dynamical downscaling with a generalized application of a "delta" approach for boundary conditions and forcing (similar to Auad et al, 2006; Liu et al. 2015; Alexander et al. 2019).

The mean difference in Boundary Conditions and atmospheric forcing between present day and future periods from multiple models was computed over 30-40 year periods and then added to the observations of the present day atmosphere, ocean and biogeochemical time series used for the existing regional ocean model hindcast. This removes the mean bias from the climate models and reduces the uncertainty in the forcing by averaging a number of models to obtain the delta values. It also allows for higher resolution spatial and temporal variability to be retained in the forcing. In order to obtain time-evolving forcing, we first compute a 30-year mean for the historical period (1980 to 2010), subtract it from the complete simulation (1980 to 2100), which is then added to a historical reanalysis. Ultimately, this produces a bias-corrected (relative to the historical period), time-evolving forcing data set that we apply to the high-resolution regional model for the projections to 2050. Given the uncertain robustness of projected changes in climate variability (Deser et al. 2012) we view correcting for bias and isolating the climate change signal through the multi-model mean as more central to this application.

Atlantic Surfclam Habitat Model

Contemporary clam habitat is specified within SEFES by ten-minute squares (TMS) using data collected in recent federal fisheries surveys and science campaigns. Past and current observations of bottom water temperatures for each TMS identified as Atlantic surfclam habitat and/or ocean quahog habitat were assembled to generate a clam habitat-model that defines boundaries of suitable habitat for both Atlantic surfclams and ocean quahogs. Both species are included in the habitat model because increasing population overlap occurs as ranges shift at differing rates for the two species, and fishery management dictates that the fishery cannot operate in areas of species overlap (Stromp et al., 2023a). Future distributions of these species were then projected based on bottom water temperatures available from the hydrodynamic forecast model.

Clam Habitat Model

Present-day conditions, defined as years 2016-2019 consistent with the SEFES model verification period (Munroe et al. 2022), were used to evaluate temperature-determined range boundaries. Present-day bottom water temperatures for each TMS were extracted from the DOPPIO implementation (López et al., 2020) of the Regional Ocean Modeling System (ROMS) (Wilkin et al., 2018; Levin et al., 2018). Biological temperature constraints derived from DOPPIO bottom water temperature estimates were obtained by extracting average monthly bottom temperatures for each TMS in the model domain for years 2016-2019. Seasons were defined as Winter (January, February, March); Spring (April, May, June); Summer (August, September, October); and Fall (October, November, December). October is included in both Summer and Fall because of the unpredictability of conditions during this month relative to the timing of the thermal stratification breakdown and erosion of the Cold Pool (Lentz, 2017; Horwitz et al., 2023). The timing and intensity of the Fall breakdown is variable, and thus differentially influences both summer and fall conditions.

For ocean quahogs, only a high-temperature range boundary was required because temperatures in the MAB are not cold enough to generate a cold-temperature range boundary for this species (e.g., Mette et al., 2016; Ballesta-Artero et al., 2017). To identify the high-temperature range boundary, TMSs in which Atlantic surfclams and ocean quahogs co-existed were identified from Northeast Fisheries Science Center (NEFSC) survey data, anecdotal information from a survey of captains, and a dedicated survey targeting this inshore boundary reported by Stromp et al. (2023b). Seasonal bottom temperatures for these TMSs for 2016-2019 representing this assumed inshore range boundary are shown in Table 1. Values in Table 1 are the averages for each of the metrics shown for the TMSs identified to define the inshore (warm temperature) range boundary. Seasonal averages are obtained by averaging the monthly values for the 3 months in each season and the 4 years of record. These metrics represent only the warmer edge of the habitat and do not describe temperature conditions for this species over the entirety of its MAB habitat. Guidance for evaluation comes from the known upper thermal limit for the species of approximately 15°C and the ability of the animals to burrow and remain burrowed for extended times (Taylor, 1976; Strahl et al., 2011), thereby avoiding highest summer/fall bottom water temperatures. This burial behavior allows ocean quahogs to be found in bottom water temperatures somewhat warmer than would be anticipated from their physiological thermal limit. Accordingly, emphasis was placed on the average across the maximum summer and fall bottom water temperatures. Based on Table 1, TMSs with a mean summer temperature less than or equal to 13.5°C were defined as habitable for ocean quahogs.

Criteria for Atlantic surfclams are more complex because designation of both the inshore (warm temperature) range boundary and the offshore (cold temperature) range boundary are required. The average seasonal bottom water temperatures for the Atlantic surfclam TMSs (Table 1) represent seasonal averages obtained by averaging the monthly values for the 3 months in each season and the 4 years of record. These TMSs were originally identified using NEFSC survey data (Munroe et al., 2022). Unlike ocean quahog habitat definition above, Atlantic surfclam TMSs are defined for the entire range rather than just the inshore boundary. Guidance for the warm temperature boundary comes from the known thermal limits for the species with temperatures above 20°C resulting in physiological stress (e.g., Munroe et al., 2013; Narváez et al., 2015; Hornstein et al., 2018). The high temperature threshold for Atlantic surfclam habitat is thus defined as summer average temperatures not exceeding 18.5°C. The cold temperature boundary is more difficult to specify because Atlantic surfclams readily survive winter temperatures of 4-5°C, yet are not found in habitats with summer temperatures much below 12°C. Therefore, three rules were established. A TMS is deemed habitable by Atlantic surfclams only if 1) summer average temperatures do not drop below 11.5°C, 2) fall average temperatures do not drop below 12°C, and 3) average spring temperatures remained above 7.5°C. The distribution of TMSs meeting these criteria showed good agreement with NEFSC survey data and data in Stromp et al. (2023b).

Table 1: *Ocean quahog and Atlantic surfclam biological habitat temperature rules. Values are the averages of all appropriate TMSs, each value being the average over 3 months per season and 4 years for that TMS.*

Species	Season	Average (°C)	Minimum (°C)	Maximum (°C)	N
Ocean Quahog	Summer	12.1	10.8	13.3	57
	Winter	8.4	6.3	9.6	57
	Spring	7.9	7.0	9.1	57
	Fall	13.3	11.3	14.3	57

Atlantic Surfclam	Summer	15.1	11.5	18.4	162
	Winter	7.0	4.1	9.9	162
	Spring	8.6	7.5	10.9	162
	Fall	13.5	12.0	15.4	162

The habitat criteria were used to designate TMSs as Atlantic surfclam and/or ocean quahog habitat but did not provide sufficient information to parameterize population dynamics processes for Atlantic surfclams, such as variation of the natural mortality rate within the occupiable range. Atlantic surfclam larvae recruited throughout the model domain and TMSs outside of Atlantic surfclam habitat were given a mortality rate of 1 yr^{-1}, which limited Atlantic surfclam survival to about 3 years in these unsuitable TMSs. A patchy distribution of the Atlantic surfclam stock within a forecast range was achieved by randomly assigning TMSs within Atlantic surfclam habitat mortality rates between 0.12 and 0.8 yr^{-1} based on the mortality rate distribution estimated by Munroe et al. (2022). This random assignment of mortality rates to Atlantic surfclam-habitable TMSs generates a patchy distribution of surfclams similar to present-day distributions.

Habitat Model Validation

Validation of the clam habitat forecast model was accomplished by comparing the contemporary habitat defined by the DOPPIO bottom temperatures to that defined for the SEFES habitat (Munroe et al., 2022), and then comparing the DOPPIO-based contemporary habitat to the contemporary habitat based on the physical model used herein. The ROMS-based DOPPIO model for years 2016-2019 was used to define seasonally averaged bottom temperature conditions for each TMS and the seasonal temperature criteria were then used to identify each TMS as Atlantic surfclam habitat or non-habitat. The resulting habitat distribution was compared to the base case used in Munroe et al. (2022), which represents present-day Atlantic surfclam distributions based on 2016-2019 stock assessment (Munroe et al., 2022). Whole-stock biomass based on habitat defined using the DOPPIO model temperatures was slightly higher (0.95 million metric tonnes, MMT) than that of the Munroe et al. (2022) base case (0.87 MMT), with both within the range estimated for biomass directly from the federal NEFSC Atlantic surfclam survey (Fig. 1; and Fig. 4a in Munroe et al., 2022). Therefore, application of the habitat model to seasonal bottom water temperatures from DOPPIO provides reliable predictions of Atlantic surfclam biomass.

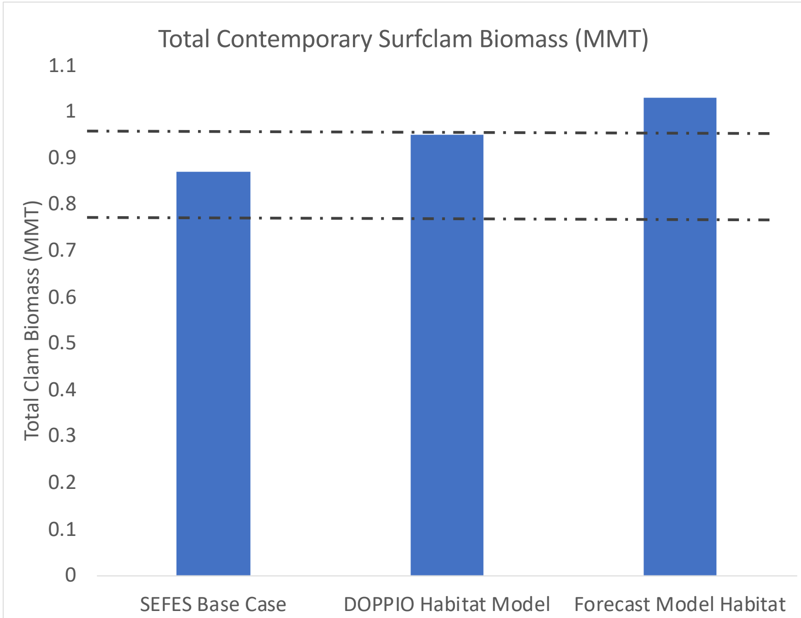


Figure 1: *Total estimated Atlantic surfclam biomass (in millions of metric tonnes; MMT) from the SEFES base case (Munroe et al., 2022) and from the habitat estimated using the simulated bottom water temperatures for current (DOPPIO) and the projected (forecast) conditions. The observed biomass estimated from the 2015 and 2019 surveys (reported in NEFSC, 2022) are indicated with dashed horizontal lines.*

The Atlantic surfclam biomass based on the habitat model using DOPPIO bottom temperature was then compared to the contemporary biomass estimated from the habitat using the forecast model. The forecast model estimated higher whole-stock biomass (1.03 MMT) than that based on DOPPIO temperatures and only slightly higher than the range of observed biomass in the federal Atlantic surfclam surveys between 2015-2019 (Fig. 1 and Fig. 4a in Munroe et al., 2022).

The incremental increase in biomass obtained from the DOPPIO forecast simulations relative to that obtained by Munroe et al. (2022) stems from two factors. First, the base case run has a few TMSs with low or no biomass due to poor survey coverage relative to recruitment events in several regions, including southern Delmarva. Second, the forecast model positions cold bottom water slightly further offshore, permitting a slightly increased habitat conducive to Atlantic surfclams relative to the habitat obtained with the DOPPIO current-day simulations. Overall, the estimates of habitat obtained with the two habitat predicting models are more comprehensive and predict slightly more habitat and in turn more biomass because they do not rely on limited survey observations as is the case for the base case (Munroe et al., 2022). These comparisons show that the simulated Atlantic surfclam distributions and stock biomasses for the 2016-2019 period provide similar habitat results, thereby the forecast model provides seasonal bottom water temperatures that can be used to develop realistic distributions of Atlantic surfclams and ocean quahogs.

Future Stock Forecasts

Future Atlantic surfclam and ocean quahog habitats are projected by decade using simulated forecast bottom water conditions and the habitat rules described above. The bias that may be generated for a given annual bottom temperature condition was minimized by representing each decade as an average across four years. The resulting habitat forecast simulations include the validated contemporary condition (2016-2019), and forecasts for the 2020s (an average of 2026-2029), the 2030s (an average of 2036-2039), the 2040s (an average of 2046-2049), and the 2050s (an average of 2052-2055) Atlantic surfclam habitat.

Each forecast consisted of 200 simulations, each with its own distribution of mortality rates within habitable TMSs and each with its own recruitment time series. Fluctuations in biomass occur in the final 50 years as the simulated Atlantic surfclam biomass oscillates about the population carrying capacity in response to variations in the distribution and intensity of recruitment and the distribution of mortality rates in the TMSs that are acceptable Atlantic surfclam habitat. Metrics used to evaluate the 50-year simulation include the calculated average and standard deviation of stock biomass in MMT, the average fishable stock biomass defined for this analysis as sizes ≥120 mm (MMT), and the spatial distribution of Atlantic surfclams and ocean quahogs within the MAB model domain, including the number of TMSs habitable by both species.

Forecast Habitat & Biomass

Forecast simulations show a change in habitat distribution in the Mid Atlantic that includes a loss of habitat supporting only ocean quahog habitat, an increase in habitat that supports both species, and an increase in habitat that supports only Atlantic surfclams (Fig. 2). Between the contemporary and 2050s conditions, a habitat that supports neither species increases marginally (16%), while habitat supporting only Atlantic surfclams increases by 36% and habitat supporting both clam species increases 152% (Fig. 3). Habitat supporting only ocean quahogs decreases substantively, declining 58% (Fig. 3).

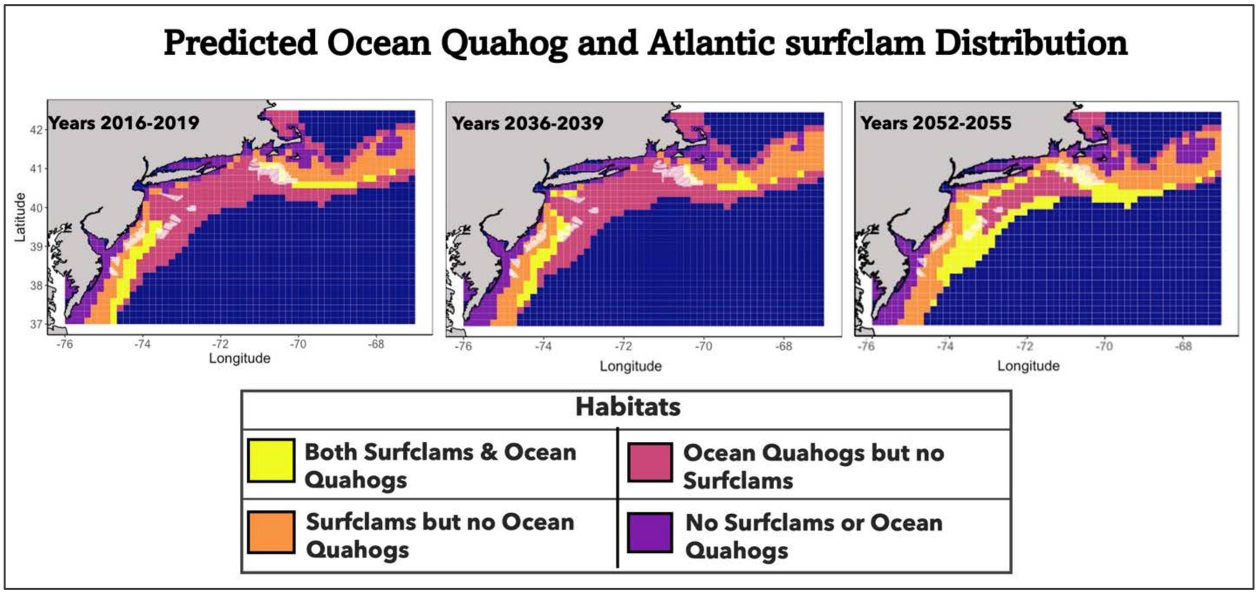


Figure 2: *Simulated clam habitat distributions based on the 50-year projections. The locations of leased offshore wind areas (white outlines) are overlaid on the TMS habitats.*

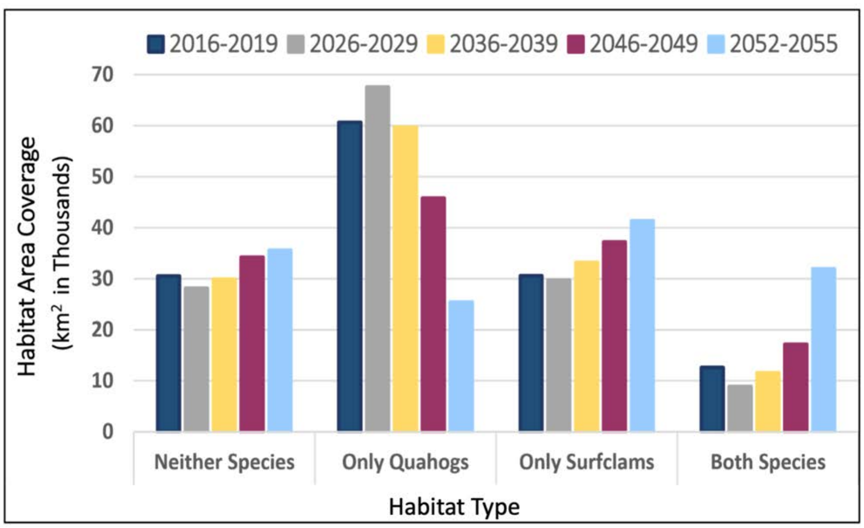


Figure 3: *Habitat area coverage over the forecast time periods (shown in different colors) by habitat type.*

These changes in habitat generate increased Atlantic surfclam biomass of 58% (total biomass) and 62% (fishable biomass) by the 2050s relative to contemporary conditions (Fig. 4). The pattern of overall increased biomass varies by region (Fig. 5). The southern-most and northern-most regions experience the smallest forecast changes, with Delmarva showing almost no change (decrease of 1%) and Georges Bank increasing by 11%. The New Jersey and Long Island regions show large increases in biomass, 130%, and 417%, respectively, and Southern New England initially decreases in biomass but will increase by 58% by 2050.

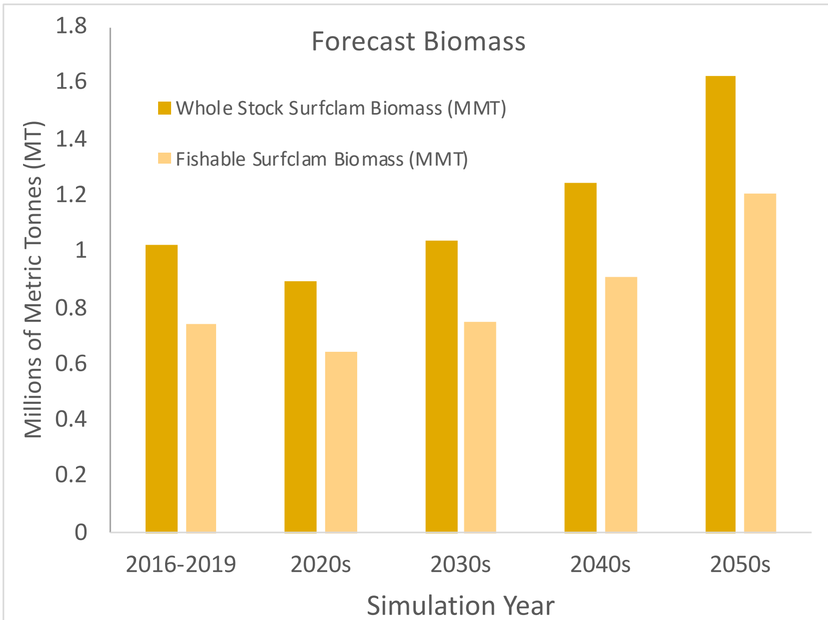


Figure 4: *Forecast Atlantic surfclam total biomass (MMT of all Atlantic surfclams) and fishable biomass (MMT of all Atlantic surfclams ≥120mm).*

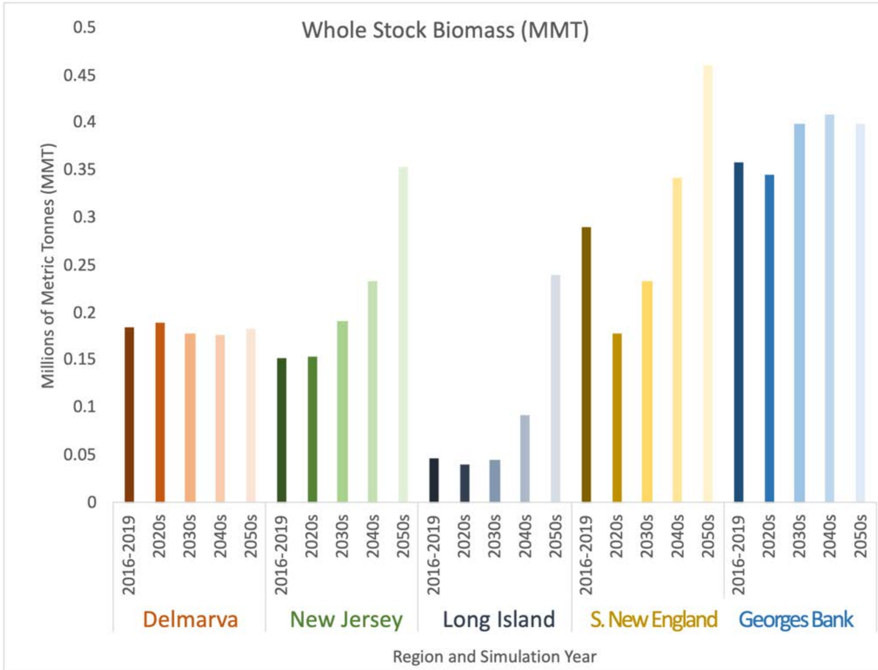


Figure 5: *Forecast simulated Atlantic surfclam biomass by fishery regions, ordered from south (Delmarva) to north (Georges Bank) and over time for each region.*

Future Fishery Forecasts

Results of projected biomass shown above can be used to inform the Atlantic surfclam fishing industry about the scope for future growth of the fishery and sustainability of regional stocks over time in response to the impacts of climate-induced warming. This response can be seen in economic metrics such as catch, Landings per Unit Effort (LPUE), and time at sea.

Fishing Fleet Simulations

SEFES simulates the Atlantic surfclam fishery within the MAB, including its economic components (Scheld et al., 2022). The simulated MAB fishing fleet is based on specifications for each of the vessels in the fishery during 2016-2019. This simulated fleet comprises 33 vessels, each with a designated homeport, and equipped with specified landing capacities, dredge sizes, vessel speeds, fuel consumption rates, and allowed times at sea which restrict fishing ground access. Each vessel is randomly assigned a captain with a range of behavioral characteristics (a total of 12 captain types), including their communication style with other fishery participants, their searching tendencies to identify new fishing grounds and their searching frequency; and their tendency to weigh the memories of past and recent catch histories to evaluate anticipated catch rates (Munroe et al., 2022; Scheld et al., 2022). Captains are re-randomized among vessels for each simulation which is an important source of variability between simulations for the same time span simulated.

Simulated captains will choose to fish in the TMS that provides the largest potential catch with the shortest time at sea, all of which is contingent on their assigned memory of past fishing history, communication style, and searching history. Weather restricts the decision to fish based on the known ability of vessels of varying sizes to fish in a range of sea states. Fishing is restricted by temperatures that affect spoilage rate of catch, and this constrains time at sea. Details are further provided in Munroe et al. (2022). The Atlantic surfclam fishery is an Individual Transferable Quota (ITQ) fishery, whereby vessels are limited in their catch, and consequently by their time spent at sea, in accordance with standard operating procedures allocating allowable catch within the fishery. Simulated fishing vessels are thus allocated no more than two trips at sea per week according to this standard. Finally, the presence of ocean quahogs limits the ambit of the fishery by requiring additional time at sea for on-deck sorting, thereby limiting LPUE. Based on reports from the fishery, a catch on deck in which ocean quahogs constituted more than 4% of the catch, would dramatically reduce time fishing: thus, a 50% catch penalty is imposed on vessels fishing in these mixed catch areas (Stromp et al., 2023a), consequently reducing available fishing grounds to the fleet while simultaneously increasing time spent in transit to find alternative TMS options.

The future simulations described above extended for 300 years, with no fishing activity in the first 100 years of each simulation to allow Atlantic surfclam populations to reach carrying capacity based on specified growth, mortality, and recruitment rates; fishing begins in year 101 (e.g., Munroe et al. 2022). During the first 50 years of fishing (101-150), the stock is fished down consistent with the fishing power of the fleet. Analysis of simulation output is based on the last 50 years of the 200 years of fishing (years 250-300) because of the long generation time (about 30 years) of Atlantic surfclams. Metrics extracted from the 50-year analysis include the average and standard deviation in fishable stock biomass (≥120 mm) in MMT, LPUE (in cages per hour fished: 1 cage=32 surfclam bushels; 1 bushel=53.2 L), catch (number of cages landed per year), fishing mortality rate (yr^{-1}), fishing vessel time at sea (days yr^{-1}), fishing vessel time spent fishing (hours yr^{-1}), and the number of trips undertaken by the fishing vessels per year. Catch and landings are equivalent, as discarding of the target species does not occur in the Atlantic surfclam fishery.

Simulation output for the overall fishery, and for five regions were compared. The regions used were those previously used by NEFSC in stock assessments (e.g., NEFSC, 2007). The southern-most region encompasses areas of northern Virginia, Delaware, and Maryland (known as Delmarva), and is partitioned from New Jersey, at Delaware Bay. Long Island, NY is separated from New Jersey at Hudson Canyon. southern New England at Block Island. The fifth region, Georges Bank, is separated from southern New England by the Great South Channel.

Fishery Forecasts

The increased simulated overall biomass (Fig. 4) results in increased fishery metrics, although the increase occurs at a slower rate relative to the increase in biomass. From the contemporary condition to the 2050s, fishery LPUE is forecast to increase by 8.5% and catch is forecast to increase by 20% (Fig. 6). This increase in catch will occur with only a 13% increase in days at sea per year (Fig. 6). The disproportionate increase in fishing biomass relative to catch translates to a 25% decrease in fishing mortality rate from f=0.020 in the contemporary case to f= 0.015 in the 2050s.

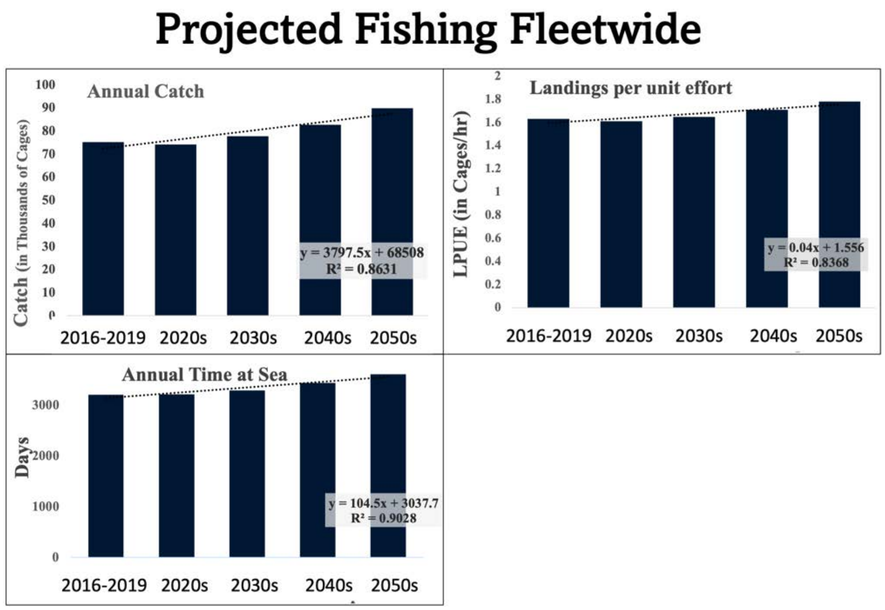


Figure 6: *Forecast Atlantic surfclam fishing metrics from simulations that used forecast habitat conditions from contemporary through the 2050s.*

Regional patterns of fishing also generally increase from contemporary conditions through the 2050s (Fig. 7), except Georges Bank where catch and time at sea decline slightly (-1% and -2% respectively), and LPUE increases slightly (2%). In the southern Delmarva region, catch and LPUE both increase by ~10% and time at sea varies through the simulations but by 2050 remains unchanged. The central regions experience the greatest increase in fishery metrics with catch increasing by 35% in New Jersey, 167% in Long Island, and 19% in southern New England (Fig. 7). LPUE also increase in New Jersey, Long Island, and southern New England; however, by a slightly lower proportion at 22%, 61%, and 12% respectively. Finally, time at sea increases by 17% in New Jersey, 132% in Long Island, and 9% in southern New England. (Fig. 7).

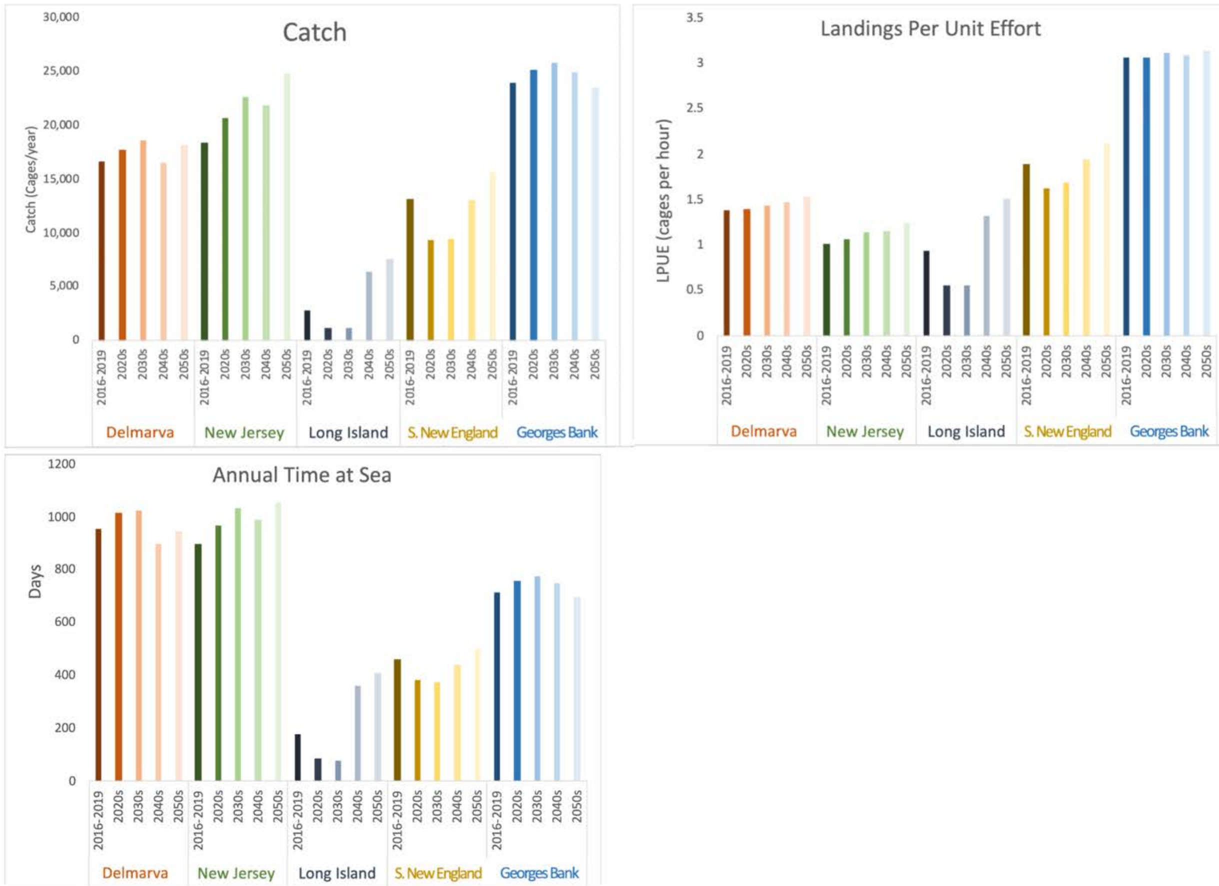


Figure 7: *Simulated Atlantic surfclam fishing metrics obtained for contemporary conditions through the 2050s, ordered from south (Delmarva) on the left to north (Georges Bank) on the right..*

Fishery and Offshore Wind Forecasts

The effect of fishing restrictions on the fleet from the presence of offshore wind lease areas was simulated for contemporary and future conditions. These fishery restrictions follow those used in previous model configurations (see Scheld et al., 2022 for more detail) with the exception that the footprints of the wind lease areas are updated to reflect the most recent spatial configuration (Fig. 8). The fishing restrictions ranged from no fishing but transit allowed in the wind lease areas (least restrictive, dark blue TMSs, Fig. 8) to no fishing and transiting through existing and future wind lease areas (most restrictive, dark and light blue TMSs, Fig. 8).

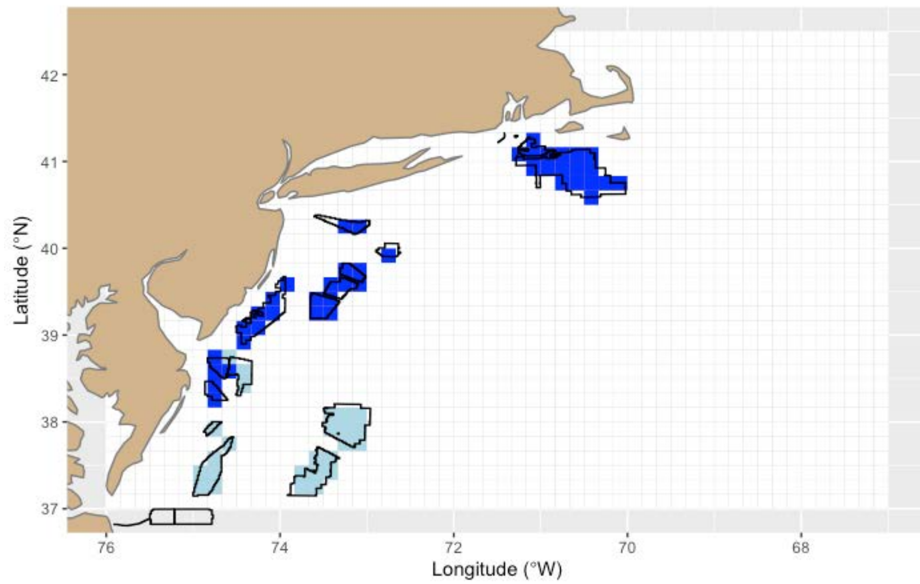


Figure 8: *Location of offshore wind lease and planning areas (outlined with black lines) in the model domain. The TMS with current offshore wind lease areas (colored in dark blue) and future wind lease areas (colored in light blue) are shown. A given TMS was designated as a wind area if >50% of the TMS overlaps with a wind lease area.*

The simulated catch decreases when restrictions related to offshore wind area locations are imposed (Fig. 9). The least restrictive conditions reduce fleetwide catch by 8% to 13%, whereas the most restrictive conditions reduce catch between 16% to 18% (Fig. 9). Catch increases over time in all simulations, including those with offshore wind restrictions, with catch in the most restrictive scenario in the 2050s reaching the unrestricted catch in the contemporary case (Fig. 9). Changes in fishery metrics vary by region, with catch, LPUE, and days fished declining in Delmarva, New Jersey, and Southern New England, while increasing in Long Island (only small changes are seen for Georges Bank; Fig. 10). Catch declined by the largest proportion for the New Jersey region (-37% for the least restrictive and -42% for the most restrictive contemporary case), with catches also dropping in Delmarva (-23%) and Southern New England (-20%) due to offshore wind restrictions (Fig. 10). Interestingly, catch increased for the Long Island region (15% for the least restrictive and 20% for the most restrictive contemporary case), due to offshore wind restrictions (Fig. 10). These regional dynamics in changes in catch are driven by displacement of the fishing effort out of wind lease areas off the coast of New Jersey and Rhode Island and into areas off Long Island (Fig. 11) where Atlantic surfclam biomass expands substantially over the forecast time period (Fig. 5).

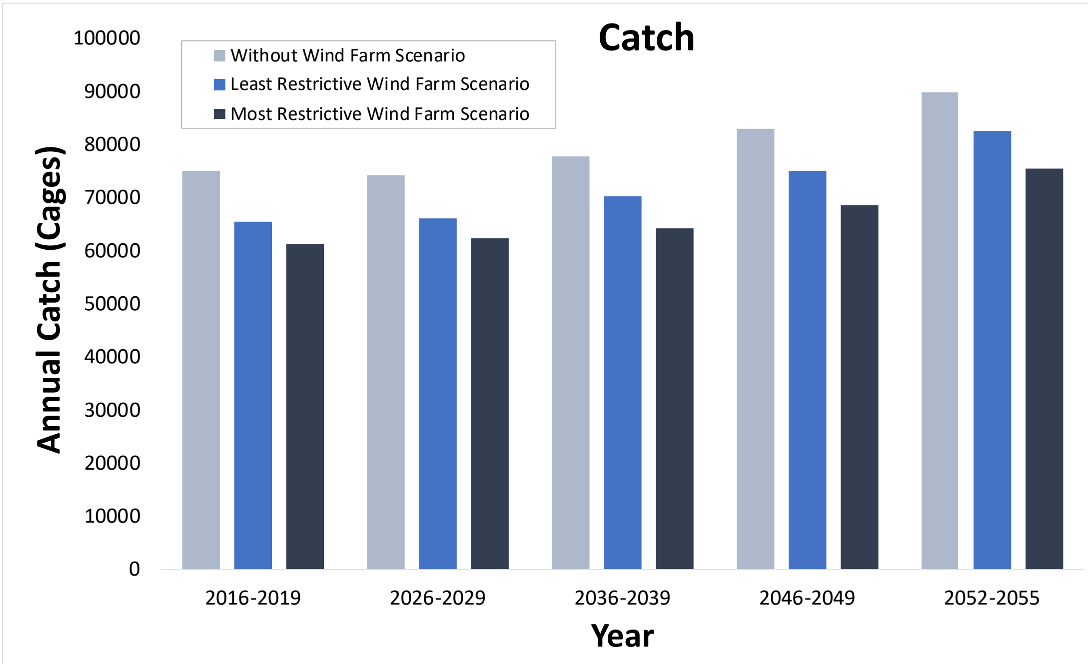


Figure 9: *Simulated Atlantic surfclam fleetwide catch in cages per year for a no offshore wind energy lease area restrictions case (light grey bars), and the least restrictive (blue bars) and most restrictive (dark grey bars) offshore wind energy area scenarios.*

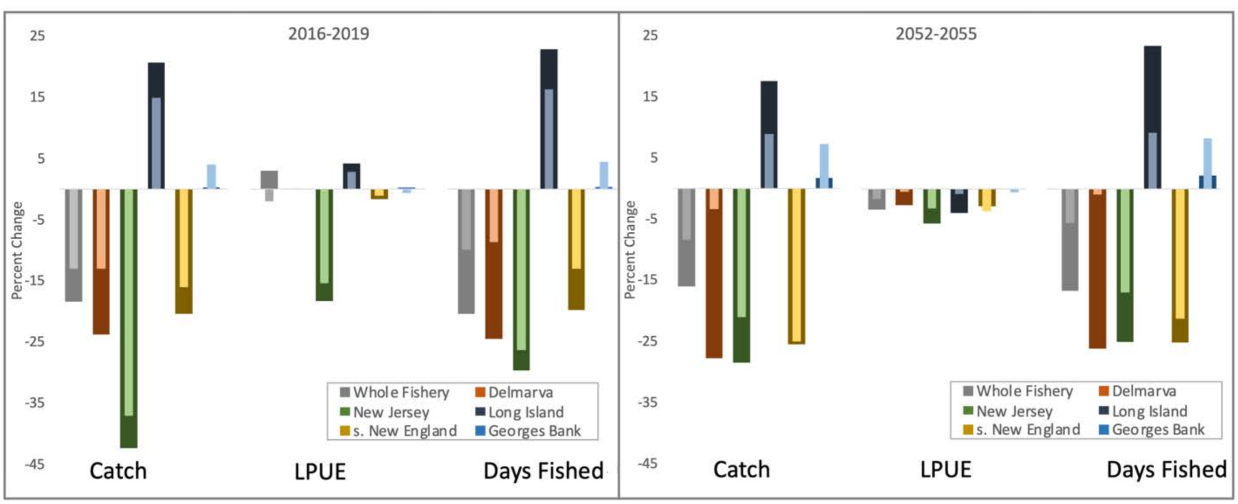


Figure 10: *Simulated percent change in fishery catch, LPUE, and days fished obtained from imposing offshore wind energy area restrictions for contemporary (left panel) and 2050s (right panel) conditions. Percent change represents differences of the least restrictive offshore wind*

scenario (lighter inset and overlaid bar) and most restrictive offshore wind scenario (darker background bar) to unrestricted fishing. Results are shows for the whole fishery (grey bars), and each region (colored by region).

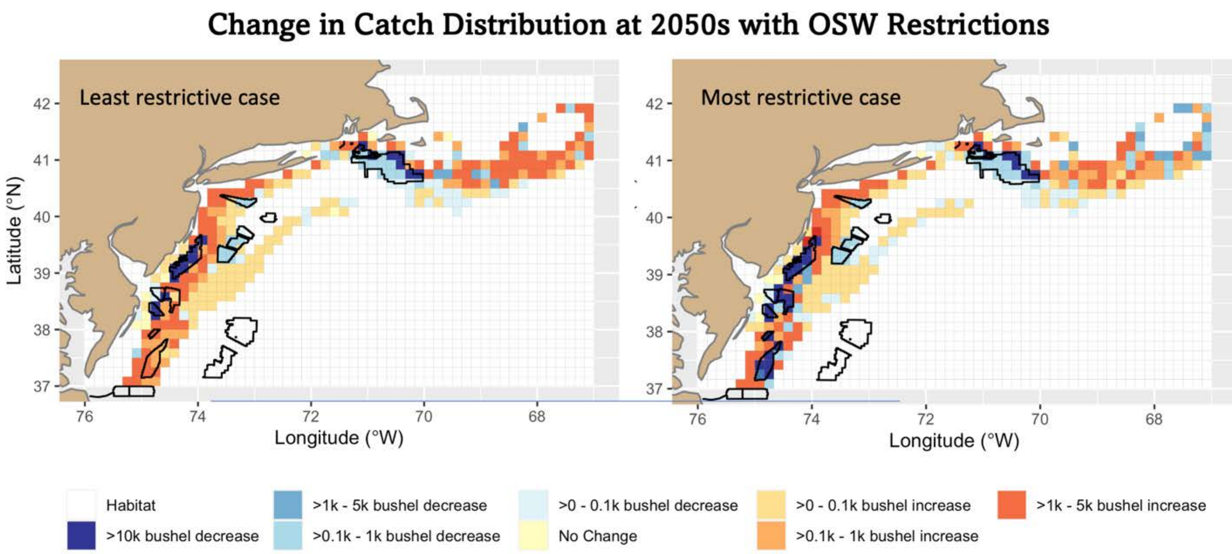


Figure 11: *Simulated patterns of change in catch by TMS for 2050 conditions obtained for the least restrictive (left panel) and most restrictive (right panel) scenarios. Blue shading shows TMSs in which catch decreases and orange shading shows TMSs with increased catch. Offshore wind lease areas are outlined with black lines.*

Summary

This analysis predicts a future surfclam fishery given projections of future resource condition while assuming a static industry. Results should be interpreted as what the fishery might look like in the future if the industry were not dynamically adjusting to changing fishing conditions. Over the last three decades, movement of the stock north and offshore has led to a northward shift in the fishing fleet and processing infrastructure (McCay et al. 2011). Changes in the relative utilization of ports may continue, driven by dynamic resource conditions. Increases in biomass leading to increases in landings per unit effort, and thus decreased fishing costs per unit output, could incentivize additional investment in fishing capacity. Presently, the fleet regularly catches under their annual quota due to constraints on demand and availability of substitute products. It is therefore unclear how the current fleet would respond to substantial increases in surfclam biomass.

The biological model projects large increases in surfclam biomass driven by range expansion. Within a given temperature regime, stock conditions are assumed to be stable, however. This approach allows for investigation of differences in approximate steady state biomass under different environmental conditions. The speed of bottom water temperature changes and the responsiveness of surfclam distribution and abundance should be further explored. Additionally, the impacts of other environmental parameters on surfclam biomass were not considered here but may be areas for future research.

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References

Alexander, M.A., Shin, S.I., Scott, J.D., Curchitser, E. and Stock, C., 2020. The response of the northwest Atlantic Ocean to climate change. *Journal of Climate,* 33(2), pp.405-428.

Amaya, D. J., Jacox, M. G., Alexander, M. A., Scott, J. D., Deser, C., Capotondi, A., & Phillips, A. S. 2023. Bottom marine heatwaves along the continental shelves of North America. *Nature Communications*, *14*(1): 1038.

Auad, G, Miller A, Di Lorenzo E. 2006. Long-term forecast of oceanic conditions off California and their biological implications. *Journal of Geophysical Research-Oceans*, 111 10.1029/2005jc003219.

Ballesta-Artero, I., Witbaard, R., Carroll, M. L., & van der Meer, J. 2017. Environmental factors regulating gaping activity of the bivalve *Arctica islandica* in northern Norway. *Marine Biology*, 164: 116.

Borsetti, S., Munroe, D. M., Scheld, A. M., Powell, E. N., Klinck, J. M., & Hofmann, E. E. 2023. Potential Repercussions of Offshore Wind Energy Development in the Northeast United States for the Atlantic Surfclam Survey and Population Assessment. *Marine and Coastal Fisheries*, *15*(1): e10228.

Borsetti, S., Munroe, D, Rudders, D, Dobson, C, Bochenek, E. 2018. Spatial variation in life history characteristics of waved whelk (*Buccinum undatum* L.) on the U.S. Mid-Atlantic continental shelf. *Fisheries Research,* 198: 129-137.

Deser, C., R. Knutti, S. Solomon, and A. S. Phillips, 2012a. Communication of the role of natural variability in future North American climate. *Nature Climate Change,* 2: 775-779.

Deser, C., A. S. Phillips, V. Bourdette, and H. Teng, 2012b. Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, 38: 527-546.

Deser, C., A. S. Phillips, M. A. Alexander, and B. V. Smoliak, 2014. Projecting North American Climate over the next 50 years: Uncertainty due to internal variability. *Journal of Climate*, 27: 2271-2296.

Drenkard, E. J., Stock, C., Ross, A. C., Dixon, K. W., Adcroft, A., Alexander, M., ... & Wang, M. 2021. Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES Journal of Marine Science*, *78*(6): 1969-1987.

Friedland, K. D., Miles, T., Goode, A. G., Powell, E. N., & Brady, D. C. 2022. The Middle Atlantic Bight Cold Pool is warming and shrinking: Indices from in situ autumn seafloor temperatures. *Fisheries Oceanography*, *31*(2): 217-223.

Hornstein, J., Espinosa, E. P., Cerrato, R. M., Lwiza, K. M. M., & Allam, B. 2018. The influence of temperature stress on the physiology of the Atlantic surfclam, *Spisula solidissima*. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 222: 66–73.

Horwitz, R., Miles, T. N., Munroe, D., & Kohut, J. 2023) Overlap between the Mid-Atlantic Bight Cold Pool and offshore wind lease areas. *ICES Journal of Marine Science*, fsad190.

Lentz, S. J. 2017. Seasonal warming of the Middle Atlantic Bight Cold Pool. *Journal of Geophysical Research: Oceans*, 122: 941–54.

Liu Y., S.-K. Lee, D. B. Enfield, B. A. Muhling, J. T. Lamkin, F. E. Muller-Karger, M. A. Roffer, 2015. Potential impact of climate change on the Intra-Americas Sea: Part-1. A dynamic downscaling of the CMIP5 model projections. *Journal of Marine Systems*, 148: 56-69,

Mette, M. J., Wanamaker Jr., A. D., Carroll, M. L., Ambrose Jr., & W. G., Retella, M. J. 2016. Linking large-scale climate variability with *Arctica islandica* shell growth and geochemistry in northern Norway. *Limnology and Oceanography*, 61: 748-764.

Munroe, D. M., Powell, E. N., Mann, R., Klinck, J. M., & Hofmann, E. E. 2013. Underestimation of primary productivity on continental shelves: evidence from maximum size of extant surfclam *(Spisula solidissima)* populations. *Fisheries Oceanography*, 22: 220–33.

Munroe, D.; D. Narvaez; D. Hennen; E. Hofmann; L. Jacobsen; R. Mann, E. Hofmann, E.N. Powell, J. Klinck. 2016. Fishing and bottom water temperature as drivers of change in maximum shell length in Atlantic surfclams (*Spisula solidissima). Estuarine Coastal and Shelf Sciences,* 170: 112–122.

Munroe, D.M., Powell, E.N., Klinck, J.M., Scheld, A.M., Borsetti, S., Beckensteiner, J. and Hofmann, E.E., 2022. The Atlantic surfclam fishery and offshore wind energy development: 1. Model development and verification. *ICES Journal of Marine Science*, 79(6): 1787-1800.

Narváez, D., D. Munroe, E. Hofmann, J. Klinck, E. Powell, R. Mann, and E. Curchitser. 2015. Long-term dynamics in Atlantic surfclam (*Spisula solidissima*) populations: The role of bottom water temperature. *Journal of Marine Systems*, 141: 136-148.

NEFSC (Northeast Fisheries Science Center). 2017. 61st Northeast Regional Stock Assessment Workshop (61st SAW) Assessment Report. *Northeast Fisheries Science Center Reference Document* 17-05, 464 p.

NEFSC (Northeast Fisheries Science Center). 2022. Management Track Assessments Completed in Spring 2020. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 22-09, 86 p.

Timbs, J.R., E.N. Powell, R. Mann. 2019. Changes in the spatial distribution and anatomy of a range shift for the Atlantic surfclam *Spisula solidissima* in the Mid-Atlantic Bight and on Georges Bank. *Marine Ecology Progress Series*, 620: 77-97.

Saba, V.S., Griffies, S.M., Anderson, W.G., Winton, M., Alexander, M.A., Delworth, T.L., Hare, J.A., Harrison, M.J., Rosati, A., Vecchi, G.A. and Zhang, R., 2016. Enhanced warming of the Northwest Atlantic Ocean under climate change. *Journal of Geophysical Research: Oceans*, 121(1): 118-132.

Scheld, A. M., Beckensteiner, J., Munroe, D. M., Powell, E. N., Borsetti, S., Hofmann, E. E., and Klinck, J. M. 2022a. The Atlantic Surfclam Fishery and Offshore Wind Energy Development: 2. Assessing Economic Impacts. *ICES Journal of Marine Science,* 79(6): 1801–14.

Strahl, J., Brey, T., Philipp, E., Thorarinsdóttir, G., Fischer, N., Wessels, W., & and Abele, D. 2011. Physiological responses to self-induced burrowing and metabolic rate depression in the ocean quahog *Arctica islandica*. *The Journal of Experimental Biology,* 214: 4223–33.

Stromp, S., Scheld, A., Klinck, J., Munroe, D., Powell, E., Mann, R., Borsetti, S., Hofmann, E. 2023a. Interactive effects of climate change-induced range shifts and wind energy development on future economic conditions of the Atlantic surfclam fishery. *Marine and Coastal Fisheries*, 15(2): e10232.

Stromp, S. L., Powell, E. N., & Mann, R. 2023b. Evaluation of the degree of co-occurrence of Atlantic surfclams (*Spisula solidissima*) and ocean quahogs (*Arctica islandica*) in the expanding Northwestern Atlantic boreal/temperate ecotone: implications for their fisheries. *Journal of Shellfish Research,* 42: 61–75.

Taylor, A. C. 1976. Burrowing behaviour and anaerobiosis in the bivalve *Arctica Islandica* (L.). *Journal of the Marine Biological Association of the United Kingdom,* 56: 95–109.

Wisner, B., Wang, Z., Sheehan, A., Guo, X., Munroe, D. 2023. Genetics, age demographics, and shell size of Atlantic surfclams from the southern edge of their range. *Estuaries and Coasts*. 47:485-493.