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THEMED ISSUE: OFFSHORE WIND INTERACTIONS WITH FISH AND FISHERIES

Interactive Effects of Climate Change-Induced Range Shifts and Wind Energy Development on Future Economic Conditions of the Atlantic Surfclam Fishery

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Abstract
Rising water temperatures along the northeastern U.S. continental shelf have resulted in an offshore range shift of the Atlantic surfclam *Spisula solidissima* to waters still occupied by ocean quahogs *Arctica islandica*. Fishers presently are prohibited from landing both Atlantic surfclams and ocean quahogs in the same catch, thus limiting fishing to locations where the target species can be sorted on deck. Wind energy development on and around the fishing grounds will further restrict the fishery. A spatially explicit model of the Atlantic surfclam fishery (Spatially Explicit Fishery

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Economics Simulator) has the ability to simulate the consequences of fishery displacement due to wind energy development in combination with fishery and stock dynamics related to the species' overlap with ocean quahogs. Five sets of simulations were run to determine the effect of varying degrees of species overlap due to Atlantic surfclam range shifts in conjunction with fishing constraints due to wind farm development. Simulations tracked changes in relative stock status, fishery performance, and the economic consequences for the fishery. Compared to a business-as-usual scenario, all scenarios with less-restrictive fishing penalties due to species overlap exhibited higher raw catch numbers but also greater reductions in revenue and increases in cost after the implementation of wind farms. This analysis serves to demonstrate the response of the Atlantic surfclam fishery to combined pressures from competing ocean uses and climate change and emphasizes the potential for economic disruption of fisheries as climate change interacts with the evolution of ocean management on the continental shelf.

The Atlantic surfclam *Spisula solidissima*, a cool-temperate species, is a benthic biomass dominant on the Northeast U.S. continental shelf. The historical range of the Atlantic surfclam extended from Cape Hatteras to Georges Bank and along the extreme inshore of the Gulf of Maine (Merrill and Ropes 1969; Palmer 1991; Hofmann et al. 2018). The Atlantic surfclam fishery produces over US$30 million in annual revenue (exvessel) and, combined with the ocean quahog *Arctica islandica* fishery ($53.6 million in annual revenue, exvessel), produces over $\$1.3 \times 10^9$ in total economic impact (Murray 2016). The Atlantic surfclam fishery operates in the Middle Atlantic Bight (MAB) and on Georges Bank (NEFSC 2022), where climate-induced warming rates are much faster than the global average (Pershing et al. 2015; Saba et al. 2016). Atlantic surfclams are particularly sensitive to elevated bottom water temperatures above 21°C and generally do not survive at temperatures above 25°C (Munroe et al. 2013; Powell et al. 2017); however, juveniles can exhibit increased temperature tolerance (Acquafredda et al. 2018). The upper thermal optimum at about 21°C is determined primarily by temperature effects on filtration rate (Munroe et al. 2013). Above this temperature, Atlantic surfclams experience rapid physiological decline, principally through reduced feeding that leads to starvation, ultimately resulting in mortality when the clams are exposed to warm temperatures for an extended period of time (Kim and Powell 2004; Weinberg et al. 2005; Narváez et al. 2015).

Warming bottom water temperatures have produced a shift in the Atlantic surfclam's range offshore into deeper water—a trend that is well documented throughout the species' range (Weinberg et al. 2005; Hennen et al. 2018; Hofmann et al. 2018; Hornstein et al. 2018; Powell et al. 2019, 2020b; Timbs et al. 2019). A northward and offshore transgression of the inshore southern range boundary likely began in the 1970s (Hofmann et al. 2018), but it was not until 2000 that a historically important mass-mortality event inshore off the Delmarva Peninsula occurred (Kim and Powell 2004). A consequence of this ongoing range shift is that the Atlantic surfclam fishery, which was originally concentrated in the southern portion of the MAB during the 1970s and 1980s (Ropes 1982), has shifted northward and offshore with the changing range of the stock through the subsequent decades (McCay et al. 2011; DeGrasse et al. 2014; NEFSC 2017; for distribution maps showing the historical range shift in the stock and fishery, see Figures 13, 14, and 34 in NEFSC 2017).

The ocean quahog, another benthic biomass dominant, is a boreal clam with a range extending into the MAB. The existence of ocean quahogs in the MAB is enabled by the cold pool, which forms when summer thermal stratification traps cold winter water along the bottom (Miles et al. 2021). The cold pool permits extension of this boreal species into latitudes that are lower than the range defined by the nearshore boreal–temperate provincial boundary (Engle and Summers 1999; Hale 2010). Ocean quahogs are most abundant at 30–60 m (Dahlgren et al. 2000) and have historically resided in waters offshore of those occupied by the Atlantic surfclam, with relatively little overlap. The previously narrow ecotone between ocean quahogs and Atlantic surfclams has expanded in recent years due to the offshore range extension of the Atlantic surfclam relative to the more stable inshore boundary of the ocean quahog (Powell et al. 2020a). The limited response by ocean quahogs to warming temperatures has been attributed to their ability to burrow deeply and estivate for extended periods, thereby escaping the warmer fall bottom water temperatures produced by summer warming and the breakdown of thermal stratification. Consequently, Atlantic surfclams are now found within the inshore range of ocean quahogs (Powell et al. 2017, 2020a), and the footprint of this overlap currently stretches over an extensive depth zone throughout much of the MAB.

Presently, commercial fishing regulations prevent vessels in the fishery from landing Atlantic surfclams and ocean quahogs in the same catch. Regulation of mixed-species landings arose after the development of the individual transferable quota system for Atlantic surfclams (Adelaja et al. 1998), which requires the landings of each species to be tracked separately (NMFS 1993). This constraint limits fishing in the MAB to locations where the species do not overlap or where the species can be sorted on deck efficiently with limited crew. Anecdotal industry advice indicates that the maximum amount of species mixing that can be efficiently sorted is one individual of one species in every 25 total clams, or 4% of the total clams caught (E. N. Powell, personal observation). The historically limited species overlap was of little economic consequence to the fishery, and the regulatory division of landings reinforced low levels of bycatch discards that were already inherent in the economic penalty imposed by the onboard sorting of species. As the range of Atlantic surfclams continues to shift offshore and the fishery targets more areas of overlap with ocean quahogs, profitability may decline and fishery discards may increase.

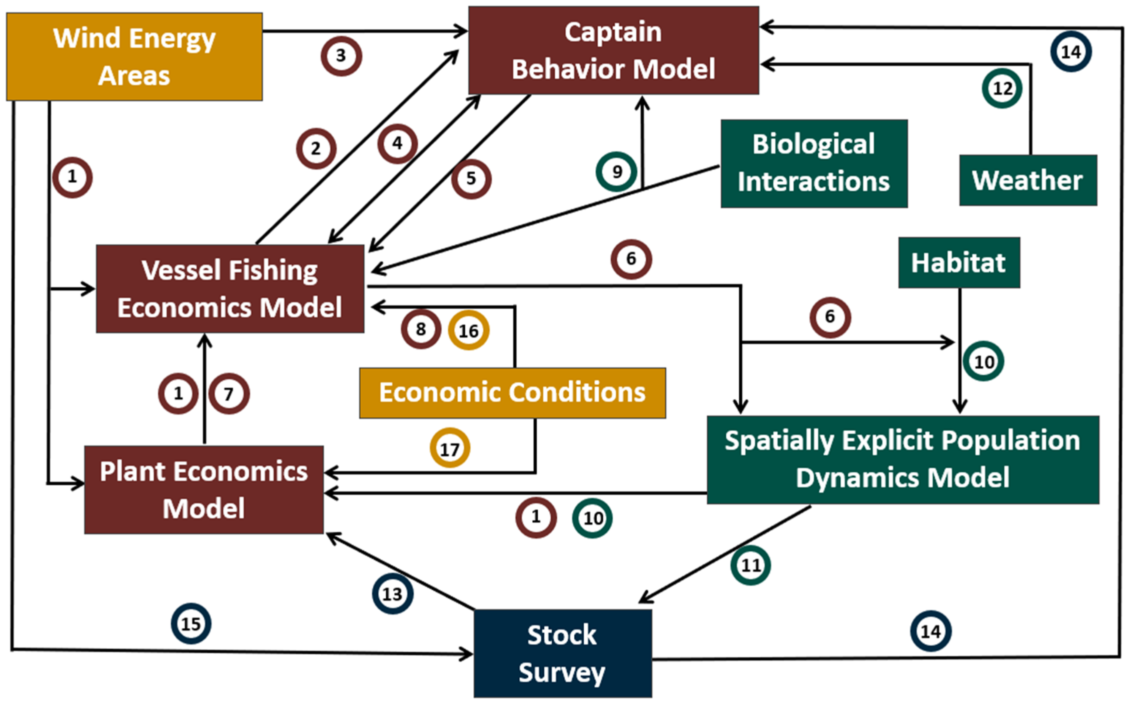
In addition to warming water temperatures that constrain the fishery's access to the Atlantic surfclam stock due to overlap with ocean quahogs, the Atlantic surfclam fishery is also vulnerable to offshore wind energy development (Kirkpatrick et al. 2017; Scheld et al. 2022). Over 930,777 ha (2.3 million acres) of the mid-Atlantic continental shelf have been leased for offshore wind energy projects (BOEM 2021; DOI 2022), which are planned to include monopile turbines on a 1.852-km (1-nautical-mile [NM]) grid (i.e., wind farms). Offshore wind is proposed for installation by 2030, including 3,411 turbines (NOAA Fisheries 2022). These leases overlap with the current distribution of the Atlantic surfclam (Munroe et al. 2022), and as a result, they represent potential ecological impacts via habitat modification and larval dispersal, as well as commercial impacts via restricted vessel operations and fishing effort displacement (Heery et al. 2017; Gill et al. 2020; Methratta et al. 2020; Negro et al. 2020). Scheld et al. (2022) projected that limitations on fishing operations and restricted vessel transit imposed by wind turbine arrays will reduce revenues for Atlantic surfclam fishing vessels and processors by approximately 3–15% and will increase average fishing costs by <1% to 5%. Conflicts between fishing and energy sectors arise as users compete for space and resources (Bidwell 2017; Haggett et al. 2020), and this is particularly true for fisheries that are dependent on sedentary marine species. The Atlantic surfclam fishery operates large vessels with hydraulic dredges (Parker 1971), making navigation through and landing of clams within wind farms challenging or impossible (Kirkpatrick et al. 2017), particularly within potential navigational and fishing corridors of 1.852 km (1 NM) or less. Economic sustainability of the Atlantic surfclam fishery hinges on the ability of the remaining available fishing grounds to support the present-day catch (Scheld et al. 2022). Much of the remaining unleased area on the MAB shelf includes depths where Atlantic surfclams and ocean quahogs now overlap. The degree to which loss of fishing grounds due to offshore wind development is likely to impair fishing operations may be influenced by the evolving overlap of the two species under the present restriction to single-species landings.

The objectives of this study were to (1) evaluate the impacts and trade-offs from the loss of fishing opportunity caused by the presence of wind farms and overlap in the distributions of Atlantic surfclams and ocean quahogs and (2) assess the potential for increased fishing opportunity afforded by landing both Atlantic surfclams and ocean quahogs together from overlap areas. The approach used was a spatially explicit, agent-based modeling framework for the Atlantic surfclam fishery: Spatially Explicit Fishery Economics Simulator (SEFES). The application of SEFES to the Atlantic surfclam fishery was described by Munroe et al. (2022). In this study, SEFES was used to evaluate five scenarios that represent a range of penalties on the Atlantic surfclam fishery that are imposed by fishing in overlap regions, which will result in a mixed catch that includes ocean quahogs. These scenarios are then evaluated to assess the additional impact of restricted fishing vessel transit and fishing opportunity imposed by wind farm placement. The simulation results provide estimation of the impacts of the competing effects of climate-induced range shifts and offshore wind energy development on the Atlantic surfclam fishery and the potential for regulatory reform to ameliorate wind farm impacts through reducing the costs of species overlap restrictions.

METHODS

Spatially Explicit Fishery Economics Simulator model.— The SEFES framework is a spatially and temporally variable model that has been used to simulate the Atlantic surfclam stock (Munroe et al. 2022), the fishery economics (Scheld et al. 2022), fishery management (Borsetti et al. 2023, this themed issue), and the impacts of variability in the behavior of fishing vessel captains and fishing fleet characteristics (Figure 1; Powell et al. 2015, 2016; Kuykendall et al. 2017, 2019). The Atlantic surfclam population dynamics model is based on federal survey data collected from 2016 to 2019. The model uses 18 length-classes at 10-mm intervals from 20 to 200 mm. Differences in geographic distribution are determined by spatial differences in natural mortality rate, recruitment, and fishing mortality (Munroe et al. 2022). The simulated population adds recruits on October 1 of each year, with the number of recruits following a standard Beverton–Holt relationship and a steepness of 0.8 (Munroe et al. 2022). Simulations of Atlantic surfclam stock distribution, fishing fleet operations, and fishery economics have undergone extensive verification using a range of empirical data resources that are detailed by Munroe et al. (2022) and Scheld et al. (2022).

The SEFES model is implemented in a domain from Georges Bank to Chesapeake Bay and extends offshore to the shelf edge. The model grid is based on 10′ latitude ×



Category	Component Processes	Property	Source
Fishery Processes			
1	Fleet dispersion	Location and movement	Fishery dependent data and stock assessment
2	Vessel characteristics: speed & capacity, dredge size & efficiency	Speed (knots), capacity (cages), dredge size (length), dredge efficiency (rate of catch)	Industry advice and 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 and fishery dependent data
8	Port location	Location (TMS)	Fishery dependent data and stock assessment
Biological & Environmental Processes			
9	Species overlap – Atlantic surfclams and ocean quahogs	Location (TMS)	Industry advice and unpublished research data
10	Biological processes: recruitment, mortality, growth, yield	Recruitment (clams per m^2), mortality (natural mortality rate), growth (shell size over time), yield (mass per size over season)	Industry advice, stock assessment, and unpublished data
11	Population structure	Length frequency and abundance by TMS	Stock assessment
12	Wind & temperature	Wind (kilometers per hour), temperature (° C)	Meteorological and airport records
Management Processes			
13	Quota, stock trends, & fishery independent data	Quota (bushels), trends (abundance and body 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 and published prices (Energy Information Administration)
17	Wholesale value	Prices by product type	Industry advice

FIGURE 1. Diagram of interactions among components in the Spatially Explicit Fishery Economics Simulator: survey and management (blue); fishing industry (red); biological interactions, including ocean quahog overlap (green); and external forces, including wind energy areas (gold). Processes acting between components are noted on black arrows and referenced in the associated legend (LPUE = landings per unit effort; TMS = 10-min [10′] square). Adapted from Munroe et al. (2022).

10′ longitude grids (10-min squares [TMSs]). The simulated Atlantic surfclam fishing fleet is represented by 33 fishing vessels, each uniquely specified in terms of fuel use, landing capacity, dredge size, and vessel speed, and the simulated vessels are representative of the existing fishing fleet (Scheld et al. 2022). Fishing vessel captains are assigned behaviors consistent with the range of known behaviors, which include the tendency to share information between captains within companies, within ports, and between ports; the tendency, spatial extent, and frequency of searching; and the degree to which recent and historical information is used to evaluate anticipated catch rates (Munroe et al. 2022; Scheld et al. 2022). Vessels are not allowed to switch ports, although historically this has occurred in the fishery (McCay et al. 2011). Fishing vessel captains choose fishing locations that are determined by the TMSs perceived to provide a full load in a minimal time at sea based on the captain's memory, as influenced by previous fishing history, searching, communication, daily temperature (affecting spoilage rate, which determines time at sea), and season (weather is influenced by season, determining the frequency and duration of trips). Vessels either remain in port, transit to or from a TMS, or actively fish for surfclams depending upon these considerations (Munroe et al. 2022). In addition, vessels are limited by quotas and time at sea to no more than 2 trips/week, consistent with the standard operating procedure within the fishery. Anticipated CPUE (cages/h fished; CPUE does not include transit time) is influenced also by the limitation on the on-deck catch processing speed in regions of overlap between Atlantic surfclams and ocean quahogs, and time at sea is influenced by transit and fishing limitations that are imposed by the presence of wind farms. For simplicity, "CPUE" in this study refers both to catch (CPUE) and landings (landings per unit effort [LPUE]) because the Atlantic surfclam fishery as prosecuted today has very limited discards of the target species.

Atlantic surfclam and ocean quahog range overlap.— The overlap regions between Atlantic surfclams and ocean quahogs were specified based on information from stock surveys and interviews with captains of Atlantic surfclam fishing vessels (Figure 2). The survey data and information provided by interviews were refined using data from a comprehensive survey of the overlap region from Hudson Canyon south to offshore Maryland, which was conducted in September 2021 (Figure 3; Powell and Mann 2021).

The TMSs where ocean quahogs are found were used to construct a mask for the simulations that considered fishing in overlap regions. A mask defines a set of TMSs of a specific type; in this paper, the ocean quahog mask defines TMSs where 4% or more of the catch consists of ocean quahogs, either by direct observation or based on captains' reports. Figure 2 shows the original mask that

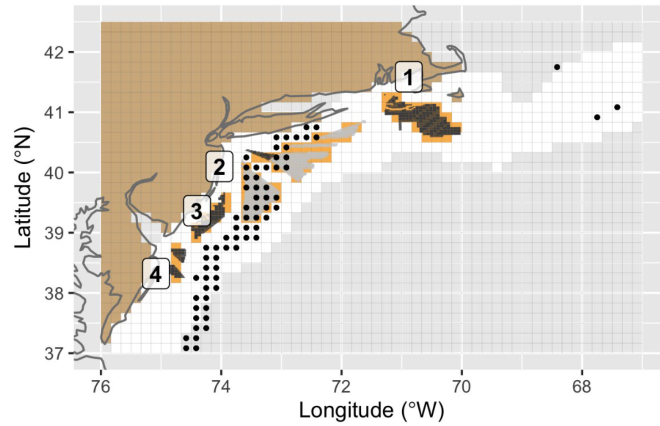


FIGURE 2. Map of the Spatially Explicit Fishery Economics Simulator model domain, showing 10-min (10′) squares with ocean quahogs (black dots), wind farm leases (dark gray), potential future wind farm leases (light gray), and grid cells around leases with restricted fishing and transit (orange). Landing ports for Atlantic surfclam fishing vessels are indicated: (1) New Bedford, Massachusetts; (2) Point Pleasant, New Jersey; (3) Atlantic City, New Jersey; and (4) Ocean City, Maryland. Figure is adapted from Scheld et al. (2022).

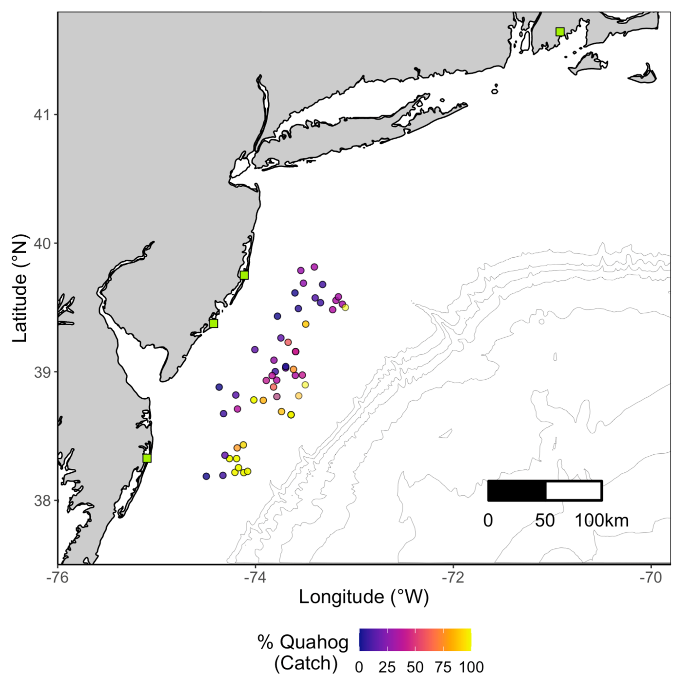


FIGURE 3. Atlantic surfclam and ocean quahog overlap from off northern Delmarva to Hudson Canyon as of September 2021. Dark-blue circles indicate locations of 100% Atlantic surfclam catch; yellow circles indicate locations of 100% ocean quahog catch. Intermediate colors on the gradient show regions in which the catch is a mix of both species. Landing ports for Atlantic surfclam fishing vessels are represented by green squares (from north to south): New Bedford, Massachusetts; Point Pleasant, New Jersey; Atlantic City, New Jersey; and Ocean City, Maryland.

was obtained from stock surveys and captains' reports and used by Munroe et al. (2022) and Scheld et al. (2022). A portion of the ocean quahog mask, the region south of Hudson Canyon, was surveyed separately in September 2021. Figure 3 shows overlap regions with a gradient of percent ocean quahog catch among sampled stations. Any locations in the survey with a mixed catch of Atlantic surfclams and ocean quahogs were applied to the existing ocean quahog mask to produce a newer, updated mask. The updated mask is used in the present simulations. In masked TMSs, a catch penalty is invoked for vessels fishing in an overlap area. The ocean quahog catch penalty is subtracted from the overall skill level of the captain. For example, the captains' skill level is set at a 60% catch efficiency (catch efficiency is recorded as the fraction of the hour fishing in which the dredge is on the bottom catching clams) in unmasked TMSs, and a 50% ocean quahog penalty imposed in masked TMSs reduces the overall skill to 10% (0.60–0.50 = 0.10). This reduced skill level was estimated based on reports from the fishery that indicated an unwillingness or inability to sort catch on deck when ocean quahogs constituted more than 4% of the catch.

Model implementation.— Five sets of simulations were used to assess the effect of changing skill level on fishing activity. In these simulations, the penalties imposed on skill level ranged from no penalty (Q0; Table 1) to a 60% penalty (Q6; Table 1), with intermediate cases of 30, 40, and 50% penalties (Q3, Q4, and Q5, respectively; Table 1). The Q5 simulations represent a "business-as-usual" scenario consistent with the standard present-day fleet behavior (Munroe et al. 2022), with the captains' skill reduced to 10% in regions of ocean quahog overlap as described earlier. These simulations, representing present-day conditions, were verified against observed fishery performance by Munroe et al. (2022). Removal of the ocean quahog mask (i.e., simulation scenario Q0) allows captains to fish in any masked TMS without an imposed ocean quahog catch penalty and thus permits an estimate of the economic cost of species overlap. For both the Q3 and Q4 scenarios, the ocean quahog penalty is reduced relative to the business-as-usual simulation scenario. The economics of the Atlantic surfclam fishery depend upon a highly mechanized fishing procedure that limits the total vessel crew. A consequence of limited crew is a limited on-deck sorting capacity. The lower penalties describe cases of improved sorting capability within the same time-at-sea constraints. Scenario Q3 imposes a penalty of 30% (0.60–0.30 = 0.30, or 30% efficiency), and scenario Q4 imposes a penalty of 40% (0.60–0.40 = 0.20, or 20% efficiency). The Q3 and Q4 scenarios were chosen to represent the potential economic investment needed to sort surfclams and ocean quahogs on deck, whether this investment is in manpower (i.e., adding an extra crew member) or in sorting technology (Bhargava and Bansal 2021). Investments assume that some flexibility exists in the degree of economic investment that is necessary to permit fishing in regions of species overlap. Scenarios Q3 and Q4, as opposed to Q0, are assumed to be potentially economically viable options balancing the cost of sorting relative to the economic gain of increased catch. A 10% or 20% penalty was not examined, as the increased on-deck sorting would require much more time or crew allocated to sorting the two species than is currently feasible while maintaining an economically viable CPUE. The final simulation scenario, Q6, raises the ocean quahog penalty to 60%, equal to the captains' skill, so that in masked TMSs, the catch efficiency is zero (0.60–0.60 = 0.00) and no Atlantic surfclams can be caught.

For each of the five simulation sets, five possible wind farm displacement conditions are considered, resulting in a total of 25 simulation scenarios (Table 2). Scenarios include no wind farm constraints on fishing or transit (00), current wind farm leases with transit allowed but no

TABLE 1. Spatially Explicit Fishery Economics Simulator model scenarios with varied ocean quahog catch restrictions and associated penalties (TMS = 10-min [10′] square).

Model scenario	Description
Q5	Business-as-usual scenario: standard fleet behavior; 50% ocean quahog penalty = one-sixth the catch of unmasked TMSs
Q0	Ocean quahog mask and penalty removed
Q3	30% penalty = one-half the catch of unmasked TMSs
Q4	40% penalty = one-third the catch of unmasked TMSs
Q6	100% penalty; zero catch efficiency in masked TMSs

TABLE 2. Spatially Explicit Fishery Economics Simulator model simulations examined to determine the impacts of ocean quahog overlap and wind farm placement on the Atlantic surfclam fishery.

Case	Offshore development	Fleet constraints
00	No wind farms	None
1 T	Current wind farm leases	Can transit; no fishing
1 N	Current wind farm leases	No transit; no fishing
2 T	Current and future wind farm leases	Can transit; no fishing
2 N	Current and future wind farm leases	No transit; no fishing

fishing (1 T), current leases without transit or fishing allowed (1 N), current and future proposed wind farm lease sites with transit allowed but no fishing (2 T), and current and future leases without fishing or transit allowed (2 N; Table 2). At this time, very limited construction of monopiles has occurred within purchased leases. Fishing vessels are currently able to fish and transit within the leases as they have always been able to do. Simulations of the effect of wind farms on the fishery assume that the leases are fully built out with monopiles sited on a 1.852-km (1-NM) grid. Restrictions on transit and fishing within leases will likely not be prohibited through federal legislation, but rather through vessel insurance policies and owner or captain preference. Only no-fishing scenarios are simulated for wind farm cases, as it is unrealistic for vessels to be able to fish within developed leases because of undersea power cables and vessel maneuverability. In Europe, where offshore wind farms are currently in operation, the use of mobile gear within leases is generally restricted (Gill et al. 2020). An Atlantic surfclam vessel fishing between turbines would need to avoid monopile support structures, rock reinforcements, and buried power cables, resulting in a lower level of efficiency compared to an unleased area (Scheld et al. 2022). Whether transit will occur is unclear; hence, simulations address both the no-transit and the transit-allowed options.

Each scenario includes 200 model runs, each of which extends for 300 years. Behaviors are randomized among captains (and vessels) in a range of combinations for each of 200 simulations for each scenario. Weather conditions are obtained by a random draw based on known weather records as described by Munroe et al. (2022), and Atlantic surfclam recruitment is based on random draws from a negative binomial distribution, resulting in a patchy distribution of surfclams among TMSs (Munroe et al. 2022). During the first 100 simulation years, Atlantic surfclam populations build to carrying capacity as determined by recruitment, growth, and natural mortality; no fishing occurs. Fishing begins in simulation year 100 and lasts for 100 years, without wind farm restrictions, to allow the stock to reach an equilibrium and to allow the captains' memories to adjust from their original specified state. Ocean quahog penalty restrictions also begin in year 100. During the final 100 years, wind farms are included for scenarios with wind energy development. For scenarios with wind farms, the wind farms are included for years 200–300. Scenarios without wind farms do not have any fishing or transit restrictions during years 200–300. The final 50 years of a simulation are used for analysis. Fishing activity and economic analyses are restricted to Atlantic surfclams; the population dynamics and fishing of ocean quahogs are not simulated. Analysis of simulation results is based on the final 50 years, providing a large set of annual observations comparable to the present-day fishery and giving the model a 50-year time frame to adjust to the presence of wind farms; however, the model does not project 50 years into the future, as the Atlantic surfclam population dynamics do not vary over the course of the simulations except for the yearly randomization of recruitment. The final 50 years are assumed to describe a 50-year history of a constant simulation case, albeit with the necessary autocorrelation imbedded in the population dynamics and the captains' behaviors. All simulation results are scaled to the business-as-usual Q5 scenario. Important considerations in this analysis are (1) the expectation that the overlap regulatory constraint will be lifted in the near future (an amendment is under consideration) and (2) the need to provide information on the economic cost of the species overlap relative to the decision by the fishery to invest in additional sorting capacity. Such comparisons can best be made against the scenario in which the fishery has full access to the stock.

Fishing activity analyses.— The average of the yearly values for the final 50 simulation years was used for analysis of economic and fishing impacts. Fishing activity metrics obtained from each simulation included total landings, LPUE (CPUE = LPUE; cages/h fishing, not total time at sea), time at sea (average per trip), time fishing (average per trip), and total trips made annually by vessels for each simulation. Vessels in the simulated fleet have landing ports in Atlantic City, New Jersey (19 vessels); New Bedford, Massachusetts (11 vessels); Ocean City, Maryland (2 vessels); and Point Pleasant, New Jersey (1 vessel; Figure 2). Vessels are also categorized into size-classes: small (≤24 m), medium (24–29 m), large (29–33 m), and jumbo (>33 m; see Munroe et al. 2022 for vessel characteristics by category). Fishing vessel time at sea is an important metric, as the fishery aims for 2 trips/week, and in warmer weather the dock-to-dock time is limited to about 48 h to prevent spoilage, except for a few of the largest (jumbo) fishing vessels. The difference in the time at sea and the time spent fishing yields the steaming time required for a round trip to the target TMS, which limits the distance from port that can be accessed by vessels of a specific size (total capacity) and speed.

Economic analyses.— Economic impacts are based on fleet revenue, total fleet cost, average cost per cage landed (standard industry conversion: 1 cage = 32 bushels; 1 clam bushel = 53.2 L), and average fuel cost per cage landed (all US$). Atlantic surfclam fishing fleet economics are derived from SEFES model output in collaboration with industry members, captains, and seafood companies that purchase and process Atlantic surfclams (Scheld et al. 2022). Economic parameters were previously assessed by Scheld et al. (2022) using Atlantic surfclam vessel trip reports for the period 2015–2019, which were obtained from the Greater Atlantic Regional Fisheries Office (National Oceanic and Atmospheric Administration

Fisheries; GARFO 2021). The price per cage landed is set to $458.75 and is based on an average of annual bushel prices from 2017 to 2019 (NEFSC 2022). Fuel prices by port are annual average prices for the New England and Central Atlantic regions, adjusted for inflation (EIA 2020). Detailed calculations for Atlantic surfclam fishing fleet revenues and costs can be found in Scheld et al. (2022; their equations 1–7).

RESULTS

Ocean Quahog Overlap Comparisons: Fishing Activity Metrics

Changes in fishing activity metrics varied across simulations with different ocean quahog penalties (Figure 4; Appendix Table A.1; Table S1 [available in the Supplement separately online]). All percentage values represent the range of fishing activity metrics across all five wind farm cases for one ocean quahog penalty simulation. The LPUE predictably declined in each simulation with an ocean quahog mask restriction compared to simulations with no mask, with LPUE declining as the ocean quahog penalty increased. The LPUE in cases with a 30% penalty were reduced by 10.24–13.84%, whereas the LPUE in cases with 40% and 50% penalties decreased by 11.63–16.66% and 12.38–18.41%, respectively. Substantial declines in LPUE for Q6 (54.39–59.77%) were likely a result of the extreme limitation in the number of fishable TMSs.

Average time at sea and time fishing increased in all simulations with an ocean quahog penalty relative to the simulations without a penalty, and greater increases in time were observed as the ocean quahog penalty increased. The number of total trips declined in all simulations with an ocean quahog penalty relative to the simulations without a penalty, again with larger penalties producing greater declines. Cases with a 30% penalty had trips reduced by 10.46–16.32%, while a 40% penalty generated 12.03–18.19% fewer trips and a 50% penalty produced 12.45–18.91% fewer trips. Fishing penalties imposed by the ocean quahog mask consequently led to shrinkage of the fishable area, while the time needed for transit increased, overall reducing the total number of trips that vessels were able to complete. The number of trips increased in the Q6 scenarios, as the few available TMSs were inshore, but the LPUE in these TMSs were very low, thus limiting the total landings.

Ocean Quahog Overlap Comparisons: Economic Metrics

Cases with greater ocean quahog penalties produced larger reductions in revenue (Figure 5; Tables A.2 and S2).

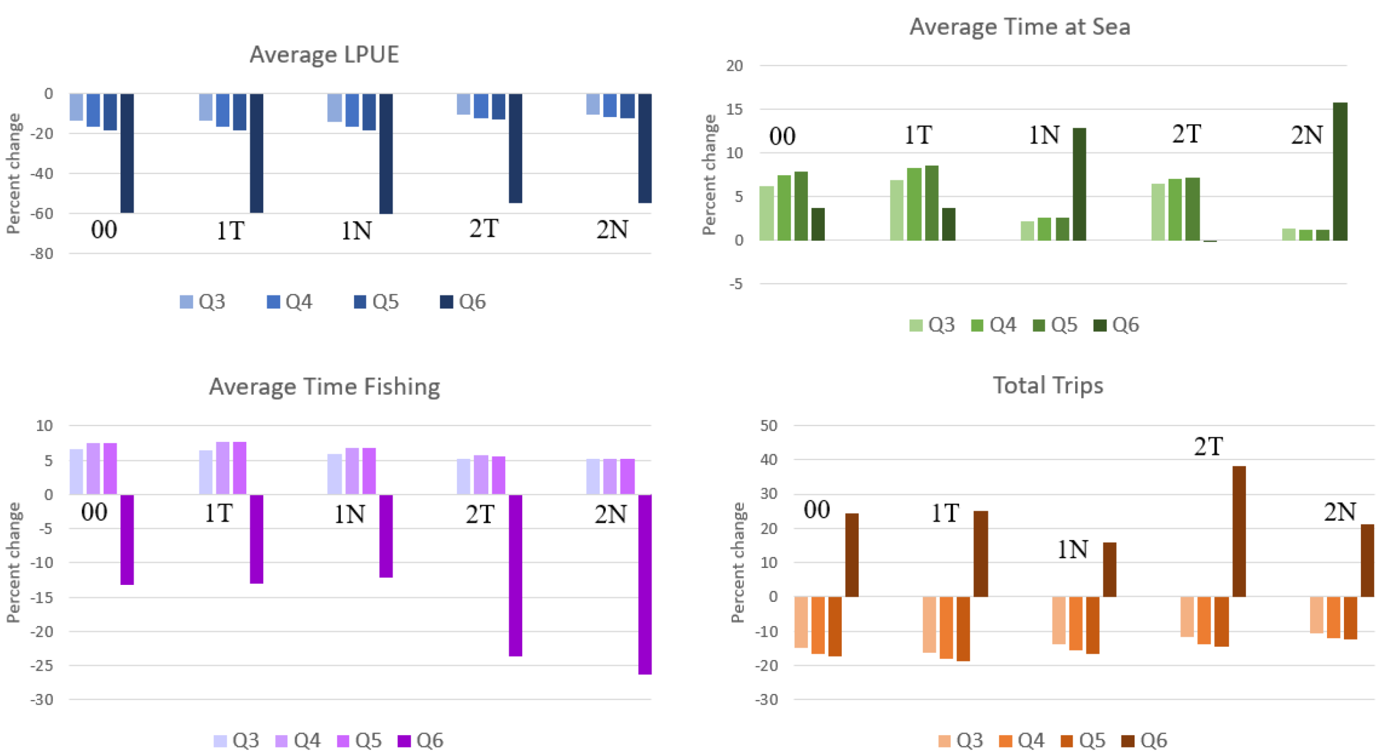


FIGURE 4. Percent change in fishing activity (landings per unit effort [LPUE], cages/h fishing; average time at sea, h/trip; average time fishing, h/trip; and total trips per year) for each ocean quahog penalty case relative to the scenario without the ocean quahog catch penalty (Q0) grouped by wind farm designation. Ocean quahog penalty codes (Q3, Q4, Q5, Q6) and wind farm case codes (00, 1 T, 1 N, 2 T, 2 N) are defined in Tables 1 and 2.

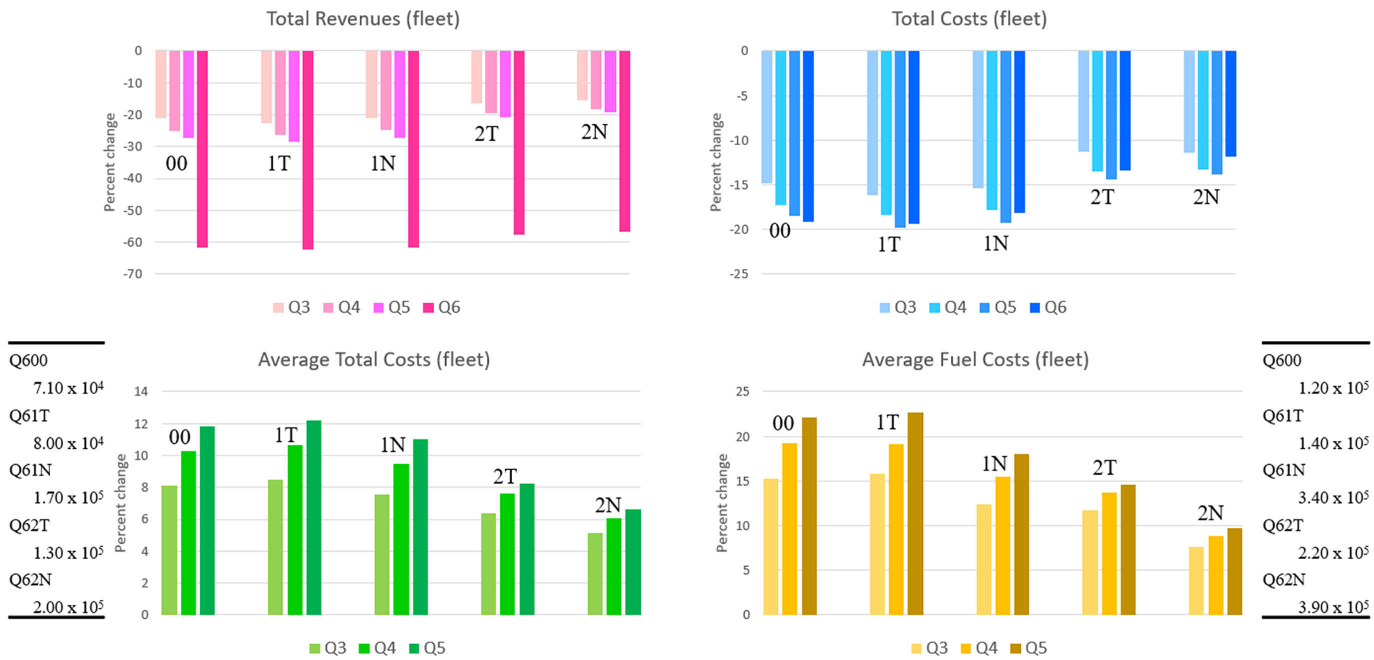


FIGURE 5. Percent change in economic metrics (total revenues, US$; total costs, \$; average total costs, \$/cage; and average fuel costs, \$/cage) for each of the Spatially Explicit Fishery Economics Simulator simulations relative to the case with no ocean quahog catch penalty (Q0) grouped by wind farm designation. Ocean quahog penalty codes (Q3, Q4, Q5, Q6) and wind farm case codes (00, 1 T, 1 N, 2 T, 2 N) are defined in Tables 1 and 2. Tables to the left of the average total costs plot and to the right of the average fuel costs plot present values for Q6 cases because they are much greater in scale. Average total costs and fuel costs were obtained by dividing totals by the number of cages landed (\$/cage; 1 cage = 32 bushels; 1 clam bushel = 53.2 L).

All percentage values represent the range of economic metrics across all five wind farm cases for one ocean quahog penalty simulation. Business-as-usual cases (Q5) declined in revenue by up to 28.56% compared to cases with no ocean quahog restrictions (Q0). Lowering the ocean quahog penalty to 40% (Q4) or 30% (Q3) reduced losses in revenue, but revenue still declined by 22.58–26.23%. Revenue dropped sharply, by up to 62.36%, with the 100% ocean quahog penalty (Q6).

Trends of decreasing revenue as the ocean quahog penalty increased were also observed for increasing costs in the metrics of average total costs (5.12–12.21%, excluding Q6; see Figure 5) and average fuel costs per cage landed (7.59–22.70%, excluding Q6; see Figure 5). Total fleet costs (operational costs) decreased as vessels spent less time fishing and took fewer trips. Lowest cost declines were observed in Q3 (11.32–16.12%), followed by Q4 (13.25–18.42%) and Q5 (13.84–19.76%). Vessels with lower ocean quahog overlap restrictions were able to spend less time transiting and complete more trips compared to vessels in scenarios with higher ocean quahog penalties. The lower fleet costs in cases with a greater ocean quahog penalty (Q5 or Q6), a product of fewer trips taken, did not offset the larger decline in landings and hence total revenue, indicating that profits were reduced.

Wind Farm Comparisons: Fishing Activity Metrics

All percentage values represent the range of fishing activity metrics across all five ocean quahog penalty cases for one wind farm designation. Compared to the business-as-usual scenario (Q5; the scenario presumed to be the ocean quahog penalty representative of present-day conditions), average LPUE increased in most cases with wind farm development (Figure 6; Tables A.1 and S3). Exceptions included cases Q02 T and Q02 N, in which LPUE decreased by approximately 3–4% relative to the Q000 case. A reduction in TMSs available for fishing due to wind farms resulted in boats targeting locations where Atlantic surfclam density was high, thus increasing LPUE but at the expense of increased time at sea.

For each wind farm case across all ocean quahog penalties, the average time at sea rose considerably when transit through wind farms was not allowed (1 N, 2 N). The greatest time spent at sea occurred in the no-transit cases that imposed the greatest wind farm footprints (Q61 N, Q62 N), where the percent increase in time at sea was 23.00% and 31.24%, respectively.

For most simulations in which no transit through wind farms was allowed, time fishing decreased, as boats were required to spend additional time traveling to and from fishing grounds. In comparison, average time fishing

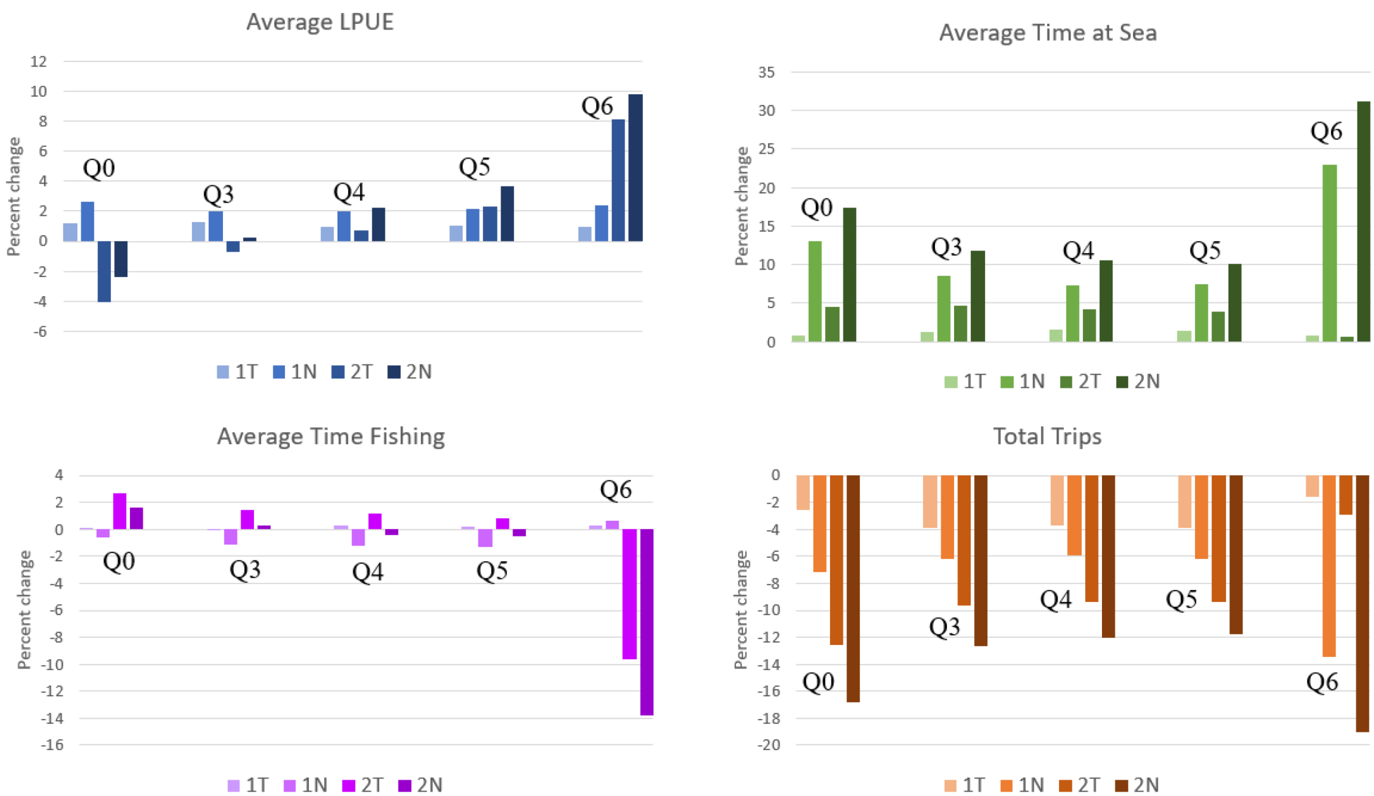


FIGURE 6. Percent change in fishing activity (landings per unit effort [LPUE], cages/h fishing; average time at sea, h/trip; average time fishing, h/trip; and total trips per year) for each wind farm case relative to the scenario without wind farms (00) grouped by ocean quahog penalty. Ocean quahog penalty codes (Q0, Q3, Q4, Q5, Q6) and wind farm case codes (1 T, 1 N, 2 T, 2 N) are defined in Tables 1 and 2.

improved in simulations that allowed transit through wind farms, becoming relatively similar to the case without wind farms (00). A glaring exception was found for Q62 T and Q62 N, in which between 9.64% and 13.78% less time was dedicated to fishing compared to the business-as-usual scenario.

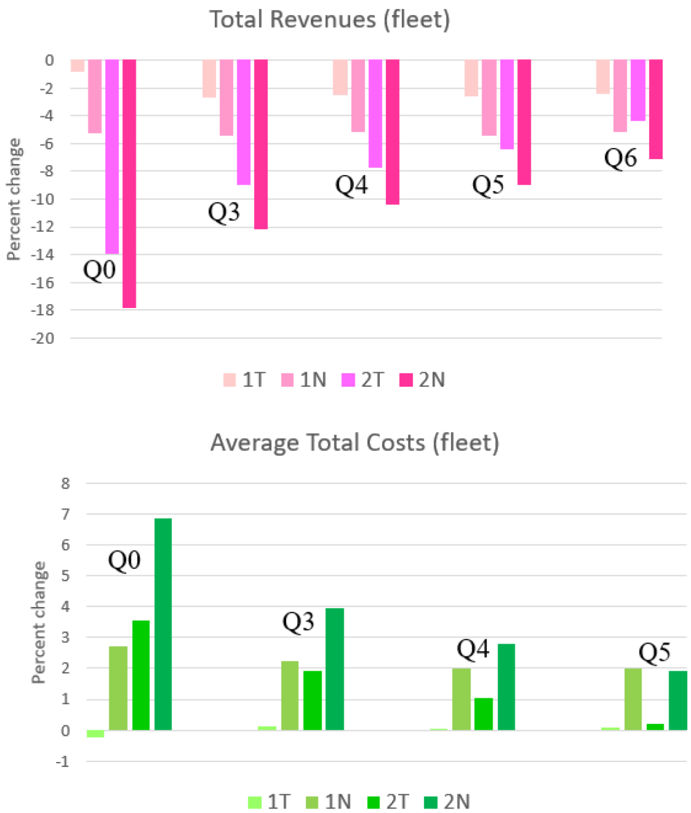
Total trips decreased in every simulation with wind farm development. Scenarios with only current leases (1 N, 1 T) exhibited between 1.56% and 13.42% fewer trips, whereas those with current and future wind farms (2 N, 2 T) produced a much greater reduction in the number of trips: 2.91–18.99%. These trends, like the others, were a consequence of reductions in fishable area and the time needed to transit around wind farms. In Q6, such few fishable TMSs existed that restricting transit (Q61 N, Q62 N) caused larger percent changes (13.42%, 18.99%) compared to the other four cases (Figure 6).

For all scenarios in which time at sea increased, the LPUE tended to increase. The inference is that captains attempt to ameliorate the penalty imposed by an increase in the required time steaming farther from port by targeting TMSs that are farther from port and that nonetheless have higher Atlantic surfclam densities. For example, in case Q42 N, the LPUE increased by 2.27%, compensating in part for a 10.56% increase in time at sea and a consequential 0.44% reduction in time fishing. The increased time at sea incurred a further penalty, however, in reducing the total trips taken by 12.02%.

Wind Farm Comparisons: Economic Metrics

Considerable differences were found when comparing economic metrics (fleet revenues, total costs, average total costs, and average fuel costs) between business-as-usual (Q500) scenarios and those with wind farms (Figure 7; Tables A.2 and S4). All percentage values represent the range of economic metrics across all five ocean quahog penalty cases for one wind farm designation. Across all simulations, total revenues declined as wind farm restrictions increased. This outcome was consistent with the reduction in the number of trips taken and the increased time at sea per trip. Cases with transit and fishing restrictions in current and future wind farms produced reductions in revenue ranging from 7.17% to 17.85% compared to cases without wind farms, whereas less-severe cases with transit allowed and only fishing restricted in current leases resulted in revenue being reduced by 0.86–2.73%.

Average total costs per cage landed for the fleet increased in every scenario except Q01 T, in which costs



Q61T	Q61N	Q62T	Q62N
11.68	142.07	90.65	207.33

Q61T	Q61N	Q62T	Q62N
12.56	195.57	91.77	270.28

FIGURE 7. Percent change in economic metrics (total revenues, US$; total costs, $; average total costs, $/cage; and average fuel costs, $/cage) for each wind farm case relative to the scenario without wind farms (00) for each set of simulations and grouped by ocean quahog penalty. Ocean quahog penalty codes (Q0, Q3, Q4, Q5, Q6) and wind farm case codes (1 T, 1 N, 2 T, 2 N) are defined in Tables 1 and 2. Tables below the plots for average total costs and average fuel costs present values for Q6 cases because they are much greater in scale. Average total costs and fuel costs were obtained by dividing totals by the number of cages landed ($/cage; 1 cage = 32 bushels; 1 clam bushel = 53.2 L).

decreased by 0.24%. The largest average total costs were found in 2 N cases (1.90–6.86%, excluding Q6; see Figure 7), followed by 1 N cases (2.01–2.72%, excluding Q6; see Figure 7). Rising costs reflected the need for boats to spend more time at sea. The same trends were identified regarding the average fuel cost per cage landed. Scenarios without transit (1 N, 2 N) displayed the highest average fuel costs (1 N: 4.44–8.15%, excluding Q6, see Figure 7; 2 N: 4.05–15.80%, excluding Q6, see Figure 7), which increased where costs were higher under future wind development. Total fleet costs, which included vessel operational costs, always decreased. Across all scenarios, total costs were lowest among 2 N and 2 T in accordance with these cases also being characterized by the largest decrease in the number of trips.

Landings

The highest landings were associated with the Q0 cases, followed by Q3, Q4, Q5, and Q6 (Figure 8; Table S5). In each set of simulations, an increment in the penalty imposed by ocean quahog overlap reduced the total landings. In each set of simulations aside from the Q6 series, landings declined once wind farms were added, and landings were further reduced when the wind farm footprint increased. Cases with no transit produced lower landings than cases with transit allowed. Interestingly, scenarios with the highest average landings, Q0, exhibited the greatest declines once wind farms were added to the simulations: a loss of 500,000 bushels landed annually between cases Q000 and Q02 N. Total losses in annual landings for the remaining cases were 250,000 bushels (Q500–Q52 N, Q300–Q32 N), 200,000 bushels (Q400–Q42 N), and 50,000 bushels (Q600–Q62 N). Landings were further reduced across all cases when transit within wind farm leases was restricted, and again the greatest declines occurred in cases with the lowest ocean quahog penalty (Figure 8; Table S5). The Q6 cases were somewhat of an anomaly because the addition of leases did not substantively reduce

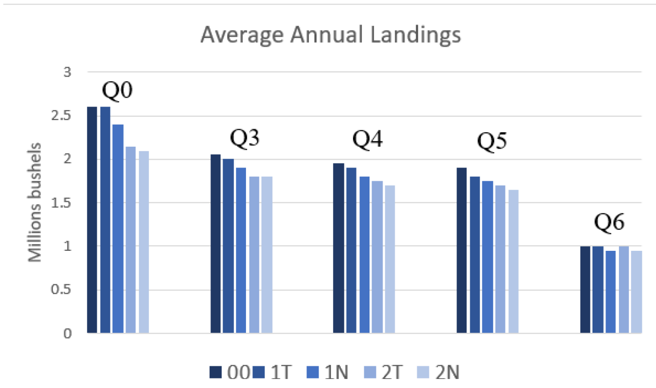


FIGURE 8. Average annual landings (millions of bushels; 1 clam bushel = 53.2 L) for each Spatially Explicit Fishery Economics Simulator case. Averages are determined across 200 simulations of each case and are reported to the nearest hundredth. Ocean quahog penalty codes (Q0, Q3, Q4, Q5, Q6) and wind farm case codes (00, 1 T, 1 N, 2 T, 2 N) are defined in Tables 1 and 2.

landings. The effect of the ocean quahog mask overwhelmed any influence of the loss of TMSs due to wind farms.

Spatial Displacement in Catch

Catch was displaced spatially among scenarios, with displacement varying between the extent of lease development and ocean quahog penalty (Figures 9–11; Figures S6 and S7 [available in the Supplement separately online]). Changes in fishing catch in this analysis occurred primarily in waters off Long Island and New Jersey, which coincide with current and future wind farms and with the portion of the fishery found to be most impacted by restrictions due to wind farms. In cases with transit allowed but no fishing (panels A and C of Figures 9–11), catch was displaced to TMSs adjacent to leases both inshore and offshore. If transit through wind farms was not allowed, catch was mainly displaced nearshore and to the north (panels B and D of Figures 9–11). Comparing cases of current lease development (1 N, 1 T) with those involving current and future lease development (2 N, 2 T) (panels A and B of Figures 9–11 versus panels C and D of Figures 9–11), fishing catch was displaced inshore off New Jersey and to the south off the Delmarva Peninsula.

Similar trends in catch displacement were also seen in scenarios with different penalties due to ocean quahog overlap (Figures 10, 11, S6, and S7). Note that in Figure 9, no TMSs were closed (Q0) due to ocean quahog overlap and vessels were able to fish further offshore and to the south. As wind farms were added and transit was restricted, catch was again shifted to northern inshore areas. Little difference was observed between simulations with reduced ocean quahog penalties (Q3, Q4). In a few TMSs, mostly south of New Jersey, catch increased in Q3 (Figure S6) in comparison to Q4 (Figure S7), likely due to greater landings in ocean quahog masked TMSs. This trend was exemplified when comparing Q3 and Q4 to the Q5 simulations, which had a higher ocean quahog penalty. Catch among the Q3 and Q4 cases was spread more evenly across the domain. Maps of catch displacement for Q6 scenarios showed a vastly reduced area of available fishing grounds (Figure 11). Once again, the same trends were observed. However, catch was condensed into just a few TMSs off New Jersey, as vessels had few options from which to choose when fishing.

DISCUSSION

Perspective

Competitive use conflicts in marine and estuarine systems, such as interactions between fisheries (Feldman et al. 2000; Powell et al. 2004; Free et al. 2021), between fisheries and habitat management options like marine protected areas (McCay 1988; Bloomfield et al. 2012; Fletcher et al. 2015; Powell et al. 2017, 2021), or between fisheries and other industries (Soniat 1988; Ruhl 2005; Abramic et al. 2021; Marín et al. 2021), are well studied. This study focuses on a more unique circumstance in which the Atlantic surfclam fishery is impacted by coincident restriction of fishable bottom by (1) a temperature-driven range shift that results in mixing of two commercial species in the offshore fishing grounds and (2) leasing of inshore fishing grounds for wind farms (Munroe et al. 2022). The Atlantic surfclam fishery is impacted incrementally by species overlap and wind farm lease restrictions, which are to a large extent additive, as the geographic overlap between the two restrictive elements is limited. Nonetheless, relaxation of the constraint imposed by the ocean quahog penalty spares some portion of the increased penalty imposed by offshore wind energy development—an opportunity that could be accessed through regulatory reform.

The Odd Interaction of Wind Farm Leases and Ocean Quahogs

In comparison to the business-as-usual cases, namely the simulations (Q5) including wind farms and the present-day fishing limitation imposed by ocean quahog overlap, simulations with no ocean quahog penalty (Q0) but with wind farms routinely displayed the highest reductions in revenue and total trips as well as the largest increases in average total costs and fuel costs ($/cage). In scenarios with a less-restrictive ocean quahog penalty (Q3, 30%; and Q4, 40%), revenues declined while costs rose, but these changes occurred to a more sizable degree in Q3. Put another way, cases with a less-restrictive ocean quahog penalty (Q0, Q3, Q4) tended to show a greater and more negative economic impact with added wind

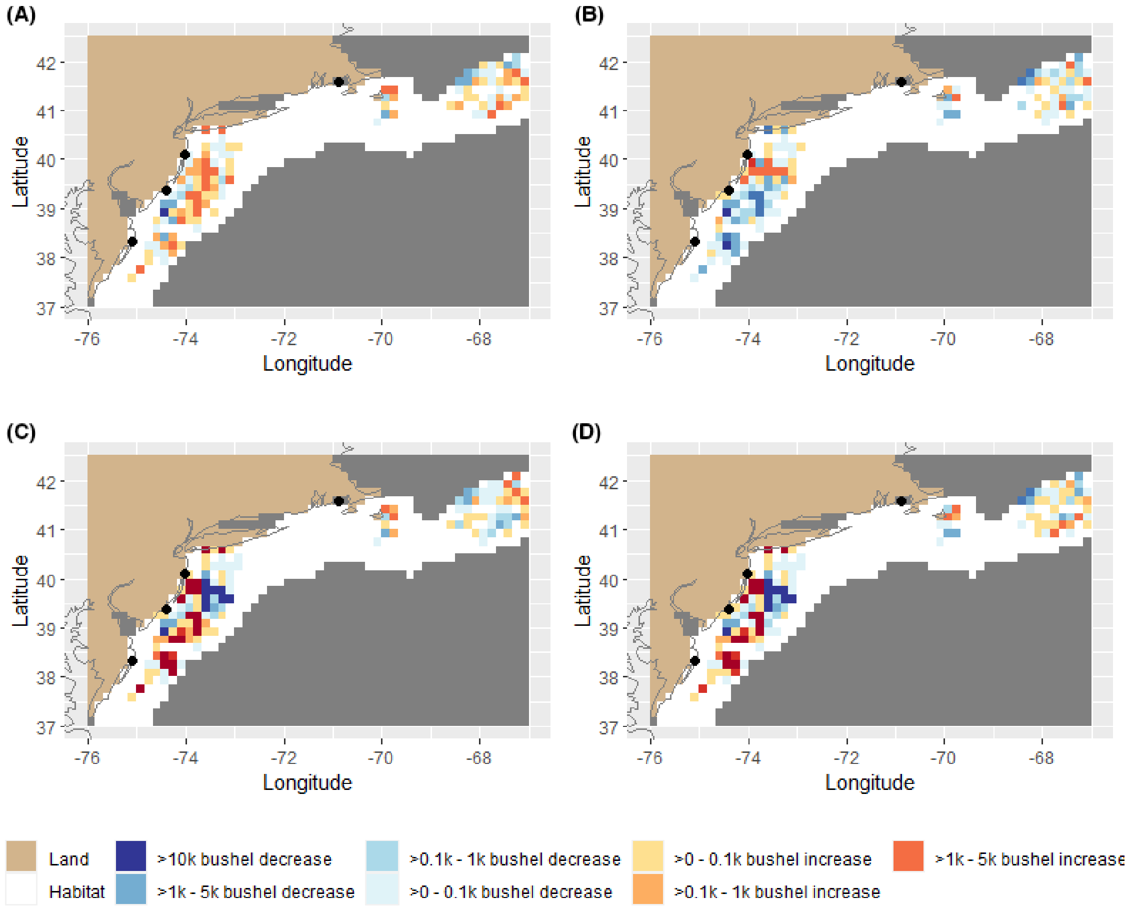


FIGURE 9. Spatial changes in catch, indicated by the change in catch per 10-min (10′) square (TMS) per year, for each wind farm case as compared to the scenario without an ocean quahog penalty and without wind farms (Q000): **(A)** current leases with transit allowed (Q01 T); **(B)** current leases with no transit (Q01 N); **(C)** current and future leases with transit allowed (Q02 T); and **(D)** current and future leases with no transit (Q02 N). Each TMS represents the difference of average catch in bushels (1 clam bushel = 53.2 L) for that TMS between specified cases. A decrease or increase in bushels indicates fewer or more landings, respectively, in that TMS.

farms compared to the more restrictive cases (Q5, Q6). In Q5 and Q6, fishable area was already greatly reduced due to ocean quahog penalties. The addition of wind farms did further constrain the available fishing footprint, but the impact was not as sizable compared to the less-restrictive cases, in which a greater reduction in spatial footprint occurred with wind farms added. Furthermore, in these less-restrictive cases, inclusion of a larger wind farm footprint (2 T, 2 N) produced greater economic impacts than a more spatially limited wind farm footprint (1 T, 1 N) compared to the more restrictive cases. Although Q3 and Q4 exhibited similar trends in fishing and economic metrics, the percent change in the 2 T and 2 N scenarios compared to the 1 T and 1 N scenarios was greatest in Q3, followed by Q4. In these cases, less-restricted fishing prior to wind farm implementation had a more substantial effect.

Percent changes in fishery and economic metrics for Q6 cases were extremely high compared to the other ocean quahog penalty scenarios. As previously noted, boats in these simulations had very few TMSs in which they could fish. Time at sea rose sharply in accordance with a substantial reduction in total trips, causing fleet and fuel costs to skyrocket. In the Q6 scenarios, all TMSs containing ocean quahogs and those containing current and future lease development were closed to fishing. Thus, boats were required to transit to the few remaining TMSs that were still fishable, and because these TMSs were farther from port, fishing time was drastically reduced.

The Sparing of Wind Farm Effects by Lowering the Ocean Quahog Penalty

These simulations explored the consequences of allowing landings of both Atlantic surfclams and ocean quahogs by reducing or eliminating the handling penalty when fishing in overlap areas (Q4, Q3, Q0). When the handling penalty was reduced from 50% to either 40% or

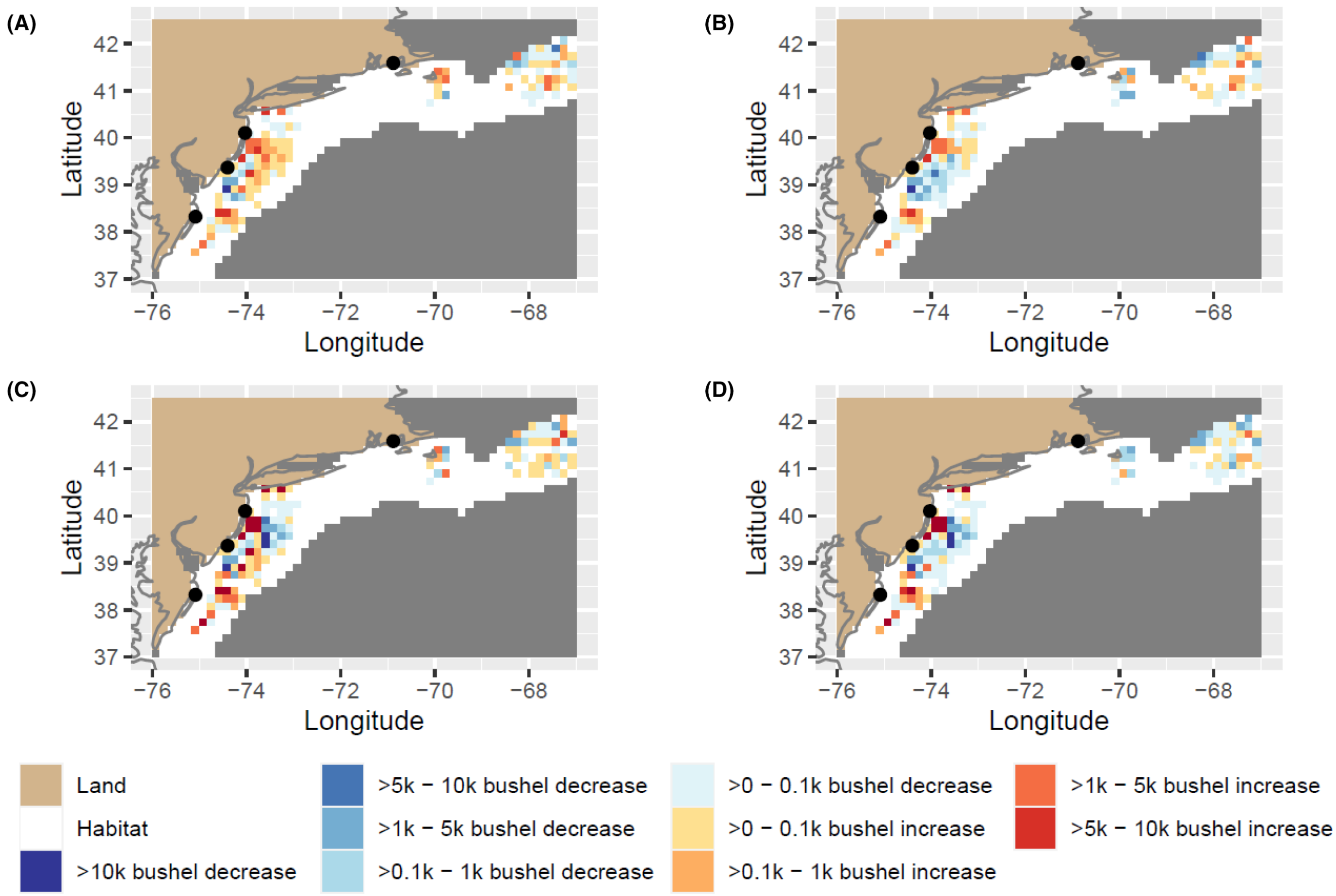


FIGURE 10. Spatial changes in catch, indicated by the change in catch per 10-min (10′) square (TMS) per year, for each wind farm case as compared to the business-as-usual scenario without wind farms (Q500): **(A)** current leases with transit allowed (Q51 T); **(B)** current leases with no transit (Q51 N); **(C)** current and future leases with transit allowed (Q52 T); and **(D)** current and future leases with no transit (Q52 N). Each TMS represents the difference of average catch in bushels (1 clam bushel = 53.2 L) for that TMS between specified cases. A decrease or increase in bushels indicates fewer or more landings, respectively, in that TMS.

30%, landings improved by 50,000 and 150,000 bushels, respectively, regardless of restrictions due to wind farm development. Vessels in the raised penalty cases spent more time at sea transiting between port and the fishing location, as their available fishing domain was constrained due to the presence of ocean quahogs, thereby reducing overall landings. However, landings losses between the no-restriction case (00) and the most restrictive case (2 N) were nearly equal (loss of 250,000 bushels) for penalties of 50, 40, and 30% (Figure 8). Fishing metrics were relatively similar among the Q5, Q4, and Q3 scenarios (Figure 4). It is possible that these cases did not produce any substantial variation in total landings from 00 to 2 N because sufficient fishable area remained available to support the prior catch levels after wind farm emplacement; nevertheless, catch was retained at an economic penalty in these cases.

Patterns of spatial displacement in catch illustrated the complex interaction of wind farm siting and ocean quahog overlap on the Atlantic surfclam fishery. Decisions about where to fish balance (1) the limited time at sea to prevent spoilage, (2) the need to achieve sufficient LPUE to fill the vessel, and (3) the need to maintain a schedule of approximately 2 trips/week (Munroe et al. 2022). The results showed that as the geographic limitations of fishable bottom grew, the number of trips declined and the time at sea increased. Depending on the spatial footprint and level of restrictions in the wind farms and the handling penalty due to ocean quahog overlap, the fleet was displaced to the north, to the south, and/or offshore. Landings per unit effort tended to be less impacted as the necessity of fishing a highly abundant TMS became even more paramount with increasing time at sea required to access TMSs farther from port. Vessels specifically targeted areas of high clam density, resulting in less of an impact on LPUE, although the time to transit to these areas was greater as the TMSs were further offshore. Nonetheless, the

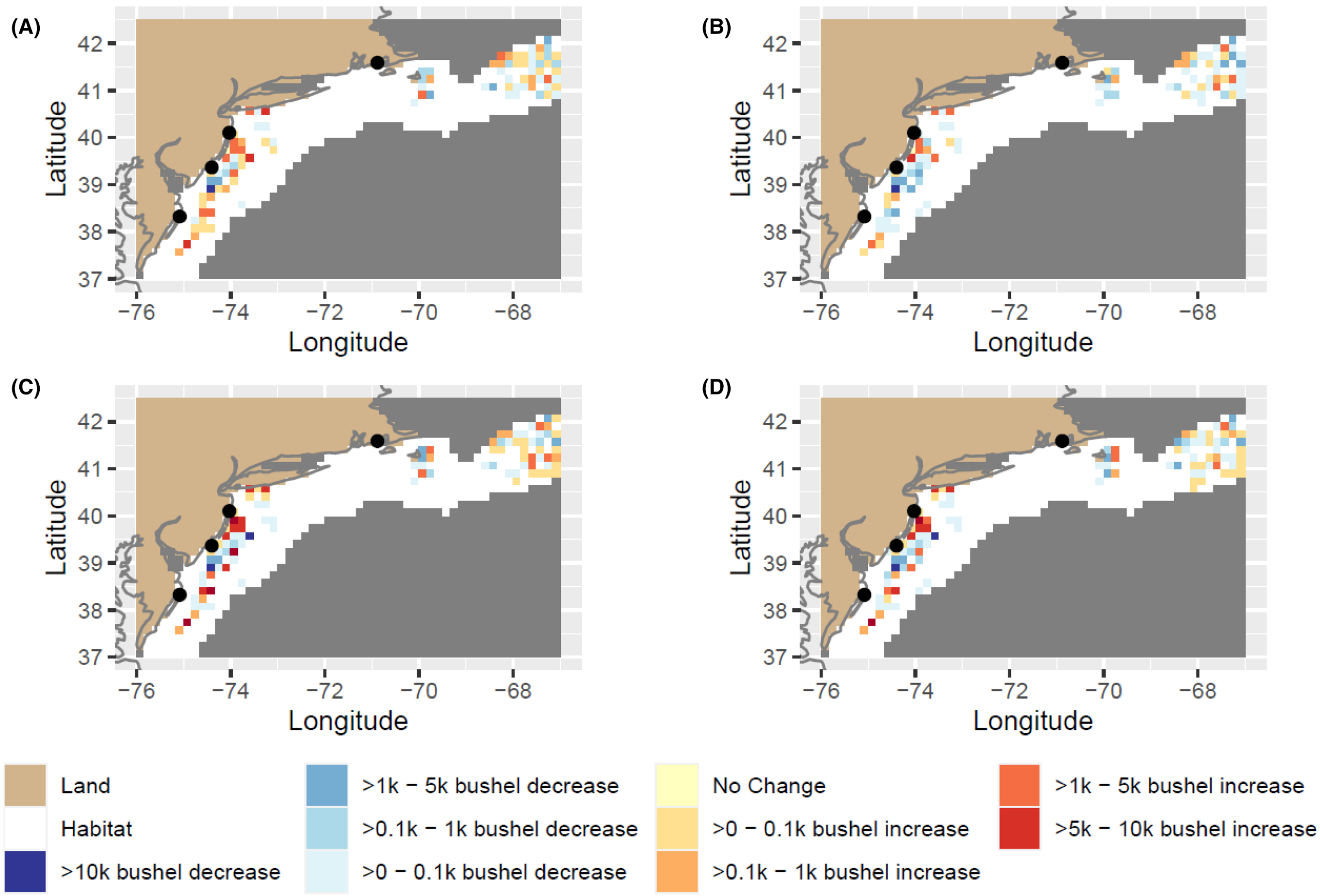


FIGURE 11. Spatial changes in catch, indicated by the change in catch per 10-min (10′) square (TMS) per year, for each wind farm case as compared to the 100% ocean quahog penalty scenario without wind farms (Q600): **(A)** current leases with transit allowed (Q61 T); **(B)** current leases with no transit (Q61 N); **(C)** current and future leases with transit allowed (Q62 T); and **(D)** current and future leases with no transit (Q62 N). Each TMS represents the difference of average catch in bushels (1 clam bushel = 53.2 L) for that TMS between specified cases. A decrease or increase in bushels indicates fewer or more landings, respectively, in that TMS.

economic impact of a reduction in trips and higher costs due to increased time at sea was not overcome by higher LPUE, and total landings declined notably as the ocean quahog penalty increased and as the geographic footprint of the wind farms expanded (Figure 7).

Climate Change, Multi-Use Management, and the Future

The northwestern Atlantic is warming more rapidly than many areas in the world's oceans (Pershing et al. 2015; Friedland et al. 2020, 2022), and marine heat waves are becoming more common (Laufkötter et al. 2020; Trisos et al. 2020). Warming of the northwestern Atlantic and the consequent shift in Atlantic surfclam populations (Hofmann et al. 2018; Powell et al. 2020b) into cooler waters outside of their historical range create new challenges in assessing the future of the Atlantic surfclam fishery. Spatial shifts in the Atlantic surfclam's range further away from ports and processing facilities have already resulted in a movement of processing capacity (McCay et al. 2011) and a shift in vessels to more northerly ports (e.g., DeGrasse et al. 2014). Hennen et al. (2018) documented the reposition of Atlantic surfclams away from their historical southern boundary through rapid mortality at the trailing edge and subsequent slower recruitment of the leading edge of the range in deeper waters. The potential limitation of food availability in deeper water remains an uncertainty (Hofmann et al. 2018), as benthic production appears to be an important component (Munroe et al. 2013) and lower surfclam condition offshore has been documented (Marzec et al. 2010). An imbalance between the rate of range contraction south and inshore and stock buildup north and offshore might be expected based on larval dispersion dynamics (Zhang et al. 2016), resulting in complex challenges to management efforts focused on ensuring that the Atlantic surfclam fishery remains economically viable.

Weather is also an important factor in determining success of the Atlantic surfclam fishery. High winds prevent vessels from making trips, while air temperatures can cause product to spoil on board (Munroe et al. 2022). Climate change may increase the frequency and duration of weather events that impact the fishery, in turn impacting the profitability of the fishery. As vessels fish at greater distances from port, the influences of weather and temperature become even more important.

Although ocean warming is generally considered a negative, one should not fail to recognize that any range shift generates winners and losers (e.g., Gormley et al. 2015; Jansen et al. 2016). In the case of the Atlantic surfclam fishery, the outcome may well hinge on the degree to which the overlap between ocean quahogs and Atlantic surfclams can be used to support increased fishing opportunity. To support such an evaluation, more information is needed on the amount of Atlantic surfclam–ocean quahog mixing that is capable of being sorted on board or at the dock and the degree to which regulatory change will permit such an outcome. The assumption used herein—that a mixture of 1 ocean quahog per 25 clams represents an upper bound for fishable conditions—has not been rigorously evaluated relative to the increased cost of sorting the two species, although increased discarding would be viewed negatively and would create a debit against the quota. Thus, landing both species together would be critical to retaining fishing grounds that would otherwise be lost due to the overlap of the two species as a product of climate change.

In Europe, offshore wind farms are more widely studied in conjunction with the impacts of a multi-use ocean. Schupp et al. (2019) characterized four types of multi-use oceans, one of which includes the coexistence of two or more involved users—in this case, wind energy and commercial fisheries. Spatial requirements overlapping between users often result in competition for the space and ensuing disputes. Research within the last two decades has indicated possibilities for multi-use management within areas of wind energy development. Lacroix and Pioch (2011) described "eco-designed" wind farms, where turbines can be used for scientific and recreational diving, tourism, and fishing. In the German North Sea, new offshore wind energy development has excluded mussel fisheries from their historic fishing grounds. Management strategies integrating wind energy with aquaculture explore options for the two sectors to negotiate on a shared-use ocean concept (Michler-Cieluch and Krause 2008). Unfortunately, the likelihood that wind farm characteristics will obviate fishing and minimize transit means that for large-scale dredge fisheries like the Atlantic surfclam fishery, any amelioration of economic impact must occur within the geographic region that is still accessible to the fishery.

Whether the Atlantic surfclam fishery can coexist with offshore wind energy development in the Northwest Atlantic remains uncertain, and whether or not a multi-use framework could even accommodate large commercial fishing vessels remains unknown. Nutters and Pinto da Silva (2012) examined the Massachusetts Ocean Management Plan, an ecosystem-based management approach serving both conservation and future development in wind energy. However, fishermen stated in interviews that the Massachusetts Ocean Management Plan approved wind farms in the middle of fishing grounds without taking the concerns of fishermen into account. Interviews with commercial fisherman were also conducted by ten Brink and Dalton (2018) in relation to the Block Island Wind Farm, the first North American offshore wind farm. The Block Island Wind Farm acted as an artificial reef to recreational fishers, who crowded the area and excluded commercial fishermen. Findings from these studies exemplify the need for expanded research on the impacts of wind energy development on ocean users and the possibilities of multi-use frameworks; they also point to the need for more careful siting to limit competitive uses and more diligent examination of alternative management strategies to minimize economic impairment.

Subsequent to the model simulations in this paper and the two preceding similar studies (Munroe et al. 2022; Scheld et al. 2022), the Bureau of Ocean Energy Management released an updated version of their planned lease areas for the outer continental shelf. Compared to the areas currently used in SEFES simulations, areas of proposed future wind energy development are reduced in size in some cases and are expanded in size in other cases. It is presently unknown how the changes in proposed lease areas will affect the results of this study. Furthermore, the potential exists for the continuing range shift of Atlantic surfclams to alter the impact of offshore wind energy development if farm siting occurs in the anticipated direction of the species' range shift. The well-documented trend in the Atlantic surfclam's range shift (Narváez et al. 2015; Hennen et al. 2018; Hofmann et al. 2018; Powell et al. 2019, 2020a) suggests continued movement of the range of the clam offshore and northward relative to many of the proposed wind farm leases.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.

APPENDIX A

FISHERY AND ECONOMIC PERFORMANCE METRICS

TABLE A.1. Fishery performance metrics for each of the 25 simulations: landings per unit effort (LPUE; cages/h fishing), average time at sea (h/trip), average time fishing (h/trip), and total trips (trips/year). Ocean quahog penalty scenario (first two digits) and wind farm case (last two digits) codes are defined in Tables 1 and 2.

	Average LPUE	Average time at Sea	Average time fishing	Total trips
Q000	1.72	39.70	23.87	2,091.67
Q300	1.49	42.24	25.43	1,784.34
Q400	1.44	42.68	25.64	1,740.54
Q500	1.40	42.83	25.66	1,727.85
Q600	0.69	41.15	20.72	2,601.97
Q01T	1.74	40.00	23.88	2,048.50
Q31T	1.51	42.78	25.42	1,714.09
Q41T	1.45	43.33	25.71	1,675.71
Q51T	1.42	43.44	25.72	1,661.05
Q61T	0.69	41.47	20.78	2,560.40

TABLE A.1. Continued.

	Average LPUE	Average time at Sea	Average time fishing	Total trips
Q01N	1.76	44.83	23.72	1,941.71
Q31N	1.52	45.84	25.14	1,671.94
Q41N	1.47	45.99	25.33	1,636.99
Q51N	1.44	46.02	25.33	1,620.55
Q61N	0.71	50.61	20.84	2,252.79
Q02T	1.65	41.49	24.51	1,827.89
Q32T	1.48	44.22	25.79	1,612.75
Q42T	1.45	44.46	25.94	1,576.85
Q52T	1.44	44.52	25.88	1,565.78
Q62T	0.75	41.42	18.72	2,526.03
Q02T	1.67	46.59	24.24	1,740.67
Q32T	1.49	47.21	25.51	1,558.51
Q42T	1.47	47.19	25.53	1,531.23
Q52T	1.46	47.18	25.53	1,523.84
Q62T	0.76	24.69	17.86	2,107.74

TABLE A.2. Economic performance metrics for each of the 25 simulations: total revenues (US$), total costs ($), average total costs ($/cage), and average fuel costs ($/cage). Ocean quahog penalty scenario (first two digits) and wind farm case (last two digits) codes are defined in Tables 1 and 2.

	Total revenues (fleet)	Total costs (fleet)	Average total costs (fleet)	Average fuel costs (fleet)
Q000	3.93×10^7	4.38×10^7	511.03	161.37
Q300	3.10×10^7	3.73×10^7	552.34	168.02
Q400	2.59×10^7	3.62×10^7	563.50	192.51
Q500	2.86×10^7	3.56×10^7	571.54	197.16
Q600	1.50×10^7	3.54×10^7	3.66×10^5	1.98 x 10^5
Q01T	3.89×10^7	4.33×10^7	509.79	160.67
Q31T	3.02×10^7	3.63×10^7	552.90	186.08
Q41T	2.88×10^7	3.53×10^7	564.19	192.78
Q51T	2.79×10^7	3.47×10^7	572.02	197.16
Q61T	1.47×10^7	3.49×10^7	4.08×10^5	2.23×10^5
Q01N	3.72×10^7	4.26×10^7	524.94	174.53
Q31N	2.93×10^7	3.60×10^7	564.73	196.08
Q41N	2.80×10^7	3.50×10^7	574.83	201.52
Q51N	2.71×10^7	3.43×10^7	582.86	205.92
Q61N	1.43×10^7	3.48×10^7	8.85×10^5	5.86×10^5
Q02T	3.38×10^7	3.90×10^7	529.10	171.84
Q32T	2.82×10^7	3.46×10^7	562.84	191.92
Q42T	2.72×10^7	3.37×10^7	569.39	195.34
Q52T	2.68×10^7	3.34×10^7	572.68	197.03
Q62T	1.44×10^7	3.78×10^7	6.97×10^5	3.80×10^5
Q02T	3.23×10^7	3.83×10^7	546.09	186.88
Q32T	2.72×10^7	3.40×10^7	574.10	201.07
Q42T	2.64×10^7	3.33×10^7	579.18	203.42
Q52T	2.61×10^7	3.30×10^7	582.42	205.25
Q62T	1.40×10^7	3.38×10^7	1.12×10^6	7.34×10^5