ICES Journal of Marine Science, 2022, **79**, 1801–1814
DOI: 10.1093/icesjms/fsac109
Advance access publication date: 20 June 2022
Original Article

ICES CIEM International Council for the Exploration of the Sea / Conseil International pour l'Exploration de la Mer

The Atlantic surfclam fishery and offshore wind energy development: 2. Assessing economic impacts

Andrew M. Scheld [1,*], Jennifer Beckensteiner [1,2], Daphne M. Munroe [3], Eric N. Powell [4], Sarah Borsetti [3], Eileen E. Hofmann [5] and John M. Klinck [5]

[1]Virginia Institute of Marine Science, William & Mary, 1370 Greate Rd., Gloucester Point, VA 23062, USA
[2]University of Brest, Ifremer, CNRS, UMR 6308, AMURE, IUEM, F-29280 Plouzane, France
[3]Rutgers the State University of New Jersey, Haskin Shellfish Research Laboratory, 6959 Miller Ave, Port Norris, NJ 08349, USA
[4]University of Southern Mississippi, Gulf Coast Research Laboratory, 703 East Beach Dr, Ocean Springs, MS 39564, USA
[5]Old Dominion University, Center for Coastal Physical Oceanography, 4111 Monarch Way, Norfolk, VA 23508, USA
[*]*Corresponding author*: tel: 1-804-684-7160; e-mail: scheld@vims.edu

The Atlantic surfclam (*Spisula solidissima*) fishery generates approximately USD 30 million in landings revenues annually, distributed across ports throughout the US Mid-Atlantic and Northeast. Overlap between areas of Atlantic surfclam harvests and offshore wind energy leasing make the fishery vulnerable to exclusion and effort displacement as development expands in the region. An existing integrated bioeconomic agent-based model, including spatial dynamics in Atlantic surfclam stock biology, heterogeneous captain behaviour, and federal management processes, was extended to incorporate costs and revenues for fishing vessels and processors and used to evaluate the potential economic effects of offshore wind development on the Atlantic surfclam fishery. Fishing activity and economic outcomes were simulated under different offshore wind energy development scenarios that impose spatial restrictions on Atlantic surfclam vessel fishing and transiting behaviour. Decreases in the number of trips and shifts in the spatial distribution of fishing effort reduced revenues for Atlantic surfclam fishing vessels and processors by ∼3–15% and increased average fishing costs by < 1–5%, with impacts varying across development scenarios and fishing ports. The modelling approach used in this analysis has potential for addressing additional questions surrounding sustainable ocean multi-use and further quantifying interactions between offshore wind energy development and commercial fisheries.

Keywords: agent-based model, Atlantic surfclam, fishing effort displacement, ocean multi-use, offshore wind energy.

Introduction

Fisheries in the Northeast and Mid-Atlantic regions of the United States are culturally and economically significant, generating nearly USD 2 billion in revenues annually and supporting over 150 000 jobs (NMFS, 2021). Many of these fisheries occur in areas that are designated for installation of large-scale wind turbine arrays to advance blue-water energy production (Methratta *et al*., 2020). As of 2021, over 1.7 million acres were leased for offshore renewable energy projects on the outer continental shelf, with the majority of leased acreage occurring in the Northeast and Mid-Atlantic (BOEM, 2021), where significant wind power potential exists (Archer and Jacobson, 2005). This anticipated expansion of offshore wind energy production on the Middle Atlantic Bight (MAB; Figure 1) continental shelf comes with considerable uncertainty in the potential impacts to the physical environment, biological resources, and dependent human communities (Gill *et al*., 2020; Haggett *et al*., 2020; Methratta *et al*., 2020; van Berkel *et al*., 2020). In particular, the economic effects of this offshore wind energy development on the US Northeast and Mid-Atlantic commercial and recreational fishing sectors are largely unknown, though preliminary analyses suggest exposure is heterogenous across fisheries and ports (Kirkpatrick *et al*., 2017).

Offshore wind development can affect fisheries and fishery resources through several pathways that include habitat alteration, changes to sound and energy landscapes, fisheries exclusion, and fishing effort displacement (Bergström *et al*., 2014; Gill *et al*., 2020). Additionally, effects on fish populations and fishing behaviour may lead to downstream impacts for fishing businesses, support services, and coastal communities (Hooper *et al*., 2018). Fishery exclusion occurs when legal restrictions on fishing activities or vessel transit within offshore wind farms exclude fishing operations, or when lack of insurance coverage, added challenges related to navigational safety, or limited coordination and cooperation among wind energy and fishing sectors lead to de facto exclusion (Gill *et al*., 2020). Changes in the spatial distribution of fishing activity, or fishing effort displacement, may occur as a result of direct or indirect exclusion, or because alternative fishing locations become more or less advantageous in response to changes in transit routes, operational considerations, or fishing conditions. Studies that provide quantitative evaluations of commercial fishery exclusion and fishing effort displacement in relation to offshore wind energy development are limited, despite these factors being frequently cited as drivers of use-conflict (Hall and Lazarus, 2015; Hooper *et al*., 2015; Haggett *et al*., 2020) and an acknowledgement that such analyses are integral to understanding the cumulative impacts of offshore wind energy development (Berkenhagen *et al*., 2010; de Groot *et al*., 2014; Gill *et al*., 2020; Haggett *et al*., 2020).

The Atlantic surfclam (*Spisula solidissima*) fishery produces over USD 30 million in ex-vessel revenues annually. Together with the fishery for the ocean quahog (*Arctica islandica*), USD 55 million in combined annual landings were estimated to

Received: November 16, 2021. **Revised:** May 5, 2022. **Accepted:** May 16, 2022

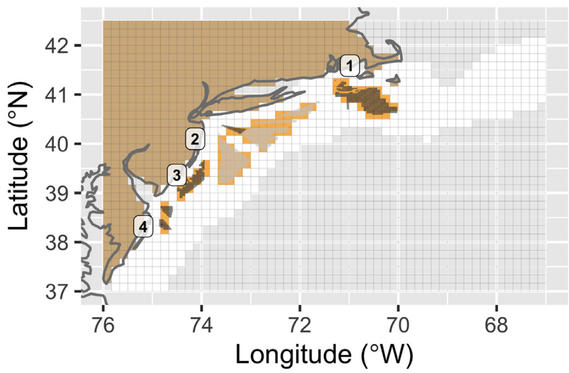

Figure 1. Map of the MAB showing existing offshore wind energy leases (dark grey) and potential future development areas (light grey). Model grid cells considered land (tan), those within the biological domain (white), and those in which fishing vessel behavioural restrictions were imposed in wind energy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

generate USD 1.3 billion in total economic impacts (Murray, 2016). The Atlantic surfclam is the target of a dredge fishery throughout its range on the MAB continental shelf and Georges Bank (Adelaja *et al*., 1998; McCay *et al*., 2011). The stock is not overfished and overfishing is not occurring (NEFSC, 2022), and since 1990 the fishery has been managed with individual transferable quotas (Wang, 1995; Rountree, 2015). Harvested Atlantic surfclams are processed into a variety of products including soups and chowders, canned minced clams, sauces, and breaded clam strips (Serchuk and Murawski, 1997). The location of harvests, key ports, and processing facilities relative to proposed wind farm areas (Figure 1), as well as the use of specialized dredge gear that may increase operational risks of fishing within wind farms, make the Atlantic surfclam fishery particularly vulnerable to impacts from offshore wind development (Kirkpatrick *et al*., 2017).

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

The objective of this study is to quantify the potential economic impacts resulting from exclusion and spatial displacement of the Atlantic surfclam fishery arising under different offshore wind energy development scenarios. The analysis uses an agent-based bioeconomic model, the Spatially explicit Fishery Economics Simulator (*SEFES*), described in Munroe *et al*. (2022) and previously used to evaluate temperature-induced range shifts in Atlantic surfclam distribution and associated effects on the stock, fishery, and management (Powell *et al*., 2015, 2016; Kuykendall *et al*., 2017, 2019). The components included in *SEFES* represent the fishable stock, fishing behaviour, structure of the fishing fleet, and economic conditions of the seafood industry. This analysis extends the results presented in Munroe *et al*. (2022) by including the economic configurations of vessels and the processing sector and using the resulting model structure to evaluate the effect of placement of offshore wind energy arrays on the overall economic conditions of the Atlantic surfclam fishery.

Material and methods

SEFES overview

The *SEFES* model framework consists of interacting, spatially explicit components (Figure 2). The model's spatial domain is structured on a grid of 10′ latitude by 10′ longitude squares (10-min squares, TMS), consistent with stock assessment survey regions as well as areas and ports utilized by the Atlantic surfclam commercial fleet.

Atlantic surfclam biomass (Fishable Stock; Figure 2) was modelled using a size-structured, spatially explicit population model. Recruitment dynamics were defined according to a Beverton–Holt relationship (Beverton and Holt, 1993), using a parameterization reflecting stock assessment observations (NEFSC, 2022) and estimates of post-settlement mortality (Timbs *et al*., 2019). Recruitment variability was introduced by applying a random factor to the total number of annual recruits. Recruitment was assumed to occur everywhere in the model domain, consistent with observations (Timbs *et al*., 2018) and larval transport modelling (Zhang *et al*., 2016). Spatially varying natural mortality rates, constructed utilizing both abundance- and age-based estimators, were applied to constrain fishable areas in the model to what is observed in the stock assessment. The population model included 18 length classes and modelled growth, or transition between length classes, using a von-Bertalanffy relationship (von Bertalanffy, 1938) and data collected through the stock assessment survey (NEFSC, 2022) and provided by Mann (unpubl. data) and Munroe *et al*. (2013). Meat yields varied seasonally according to a fifth-order polynomial that was estimated using seasonal catch records provided by industry members (Powell *et al*., 2015).

Removal of the fishable stock was done by simulation of fishing vessels assigned a captain who made decisions regarding where, when, and how to fish (Fishing; Figure 2). Captains maintained memory logs of location-specific landings per unit effort (LPUE) that update following fishing trips, searching behaviour, and communication with other captains. Communication was implemented probabilistically at the end of a fishing trip, such that captains from the same company and port shared 75% of information on fishing trip LPUEs, captains from the same port but different companies shared 50% of this information, and captains from different ports shared only 25% of information. Captains varied in terms of their searching behaviour and use of historical landings information in updating the LPUE memory log. The model employed a decision-rule utilizing captains' memories in choosing where to fish, such that the selected fishing location minimized the sum of fishing time, or time to fill its cages based on expected

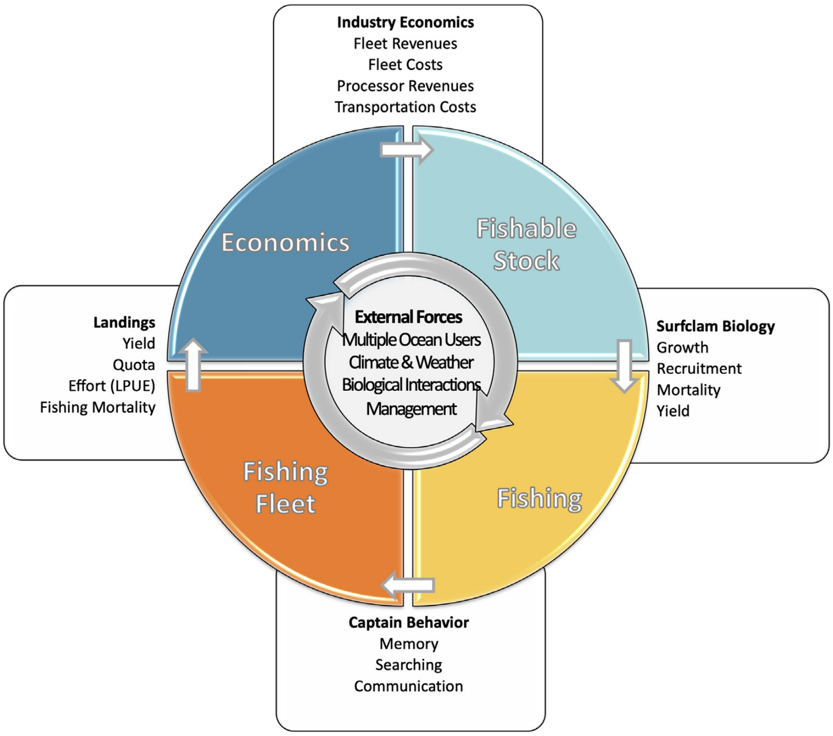

Figure 2. Components included in *SEFES* represent the Fishable Stock (light blue), Fishing (yellow), Fishing Fleet (orange), and Seafood Industry Economics (dark blue). The primary processes that determine each component and links between components (outside boxes) and the external forces that affect all model components (inner circle) are shown. The model component representing economic conditions of the seafood industry is described here. Details of other model components are provided in Munroe *et al.* (2022).

catch rates informed by the memory log, and inbound travel time. On occasions when no locations existed for which the captain believed their vessel could fill its cages and return to port within the allowed trip duration, no trip was taken. These heuristics reflect how decisions are made in the present fishery and were informed through conversations with vessel captains and industry members. Output from the *SEFES* model has been found to be relatively robust in sensitivity analyses conducted to explore variations in captain behaviours and decision-making (Powell *et al.*, 2015, 2016; Munroe *et al.*, 2022).

The fishing fleet (Figure 2) consists of vessels, each with an assigned speed, fuel use, dredge width, and landing capacities, that reflect the existing Atlantic surfclam fishing fleet based on information provided by industry partners. Vessels were grouped into size classes based on hull length, with 11 vessels categorized as small (≤ 24 m), 10 as medium (24–29 m), eight as large (> 29–33 m), and four considered jumbo (> 33 m). Meteorological buoy data were used to calculate the probability of winds in specified speed ranges and simulate weather during each simulation day. A vessel was restricted from leaving port or forced to return early from a trip if winds were above the threshold set for the vessel size class. Maximum trip duration varied by size class as well as seasonally due to catch spoilage concerns, with shorter maximum duration trips during the summer. The majority of fishing locations on Georges Bank could be reached only by jumbo vessels due to distance and trip duration constraints, which aligns with observations of the current fleet.

Fishery independent and fishery dependent information were used to validate and assess the simulations. Simulated biomass, catch, and effort from a set of 200 model runs were evaluated using corresponding measures from the federal stock assessment (see Figure 4, Munroe *et al.*, 2022). The mean simulated biomass (0.82 million metric tonnes) fell between the two most recent biomass estimates available from the assessment (0.95 mmt in 2016 and 0.79 mmt in 2019; NEFSC, 2022). Aggregate annual simulated catch (mean of 2.10 million bushels) was slightly below catch reported in the stock assessment (2.14–2.44 million bushels, 2015–2019), while average simulated hours fished per trip was within the reported range (simulated mean of 26.65 h trip^{-1} compared with 22.37–26.97 h trip^{-1} reported in stock assessment for 2015–2019). Average LPUE from the model (1.52 cages h^{-1}) also fell between values reported in the assessment (1.28–2.06 cages h^{-1}, 2015–2019). Spatial validation of stock abundance, catch, and fishing effort was done using qualitative comparisons of the observed and simulated distributions (Figures 5 and 8, Munroe *et al.*, 2022). Additionally, substantial overlap was found between distributions of trip-level values for time at sea, catch, LPUE, and the fraction of cage capacity filled per fishing trip when comparing model output to 2015–2019 trip report data provided by NOAA (GARFO, 2021). Further description of model structure, parameterization, and validation is given in Munroe *et al.* (2022).

Seafood industry economics in SEFES

The economic component included in *SEFES* (Figure 2) was used to simulate revenues and costs for fishing vessels and processors and was developed in collaboration with Atlantic surfclam industry members representing four major seafood companies that purchase and process 80–90% of Atlantic surfclam landings (Atlantic Capes Fisheries, La Monica Fine

Table 1. Fishing vessel characteristics provided by Atlantic surfclam industry members by vessel size class (small ≤ 24 m, medium 24–29 m, large > 29–33 m, and jumbo > 33 m). Crew size, fuel use when steaming and fishing, and the % of annual trips taken that targeted Atlantic surfclams are shown for each fishing vessel size class as mean values and standard deviations (italics). The number of fishing vessels in each size class is shown.

Vessel size class	Crew size (number)	Fuel steam ($\mathrm{l\ h^{-1}}$)	Fuel fish ($\mathrm{l\ h^{-1}}$)	Targeted trips (%)
Small ($n = 11$)	3.55	86.38	132.15	100.00
	0.52	*39.22*	*61.13*	*0.00*
Medium ($n = 10$)	3.60	138.92	190.41	86.00
	0.52	*42.62*	*41.34*	*30.00*
Large ($n = 8$)	4.25	198.28	287.69	71.00
	0.46	*49.44*	*98.23*	*41.00*
Jumbo ($n = 4$)	4.75	266.87	300.94	75.00
	0.50	*55.42*	*57.77*	*29.00*

Foods, Sea Watch International, and Surfside Foods; estimate based on vessel trip report data described below). Discussions with captains of eleven Atlantic surfclam fishing vessels provided information on fishing strategies and decision-making processes, vessel costs, and vessel maintenance schedules. Additional information about fishing vessel costs related to maintenance and insurance were provided by a representative from one major seafood company for seven vessels in the Atlantic surfclam fishing fleet. Summary data of responses by captains of Atlantic surfclam and ocean quahog fishing vessels to a 2011 cost survey administered by the Northeast Fisheries Science Center (NEFSC) were provided by the NEFSC's Social Sciences Branch and used to assess economic parameterizations. Vessel trip reports from 2015 to 2019 for the 33 Atlantic surfclam fishing vessels that makeup the fishing fleet (see Table 1 in Munroe *et al.*, 2022) were obtained from NOAA Fisheries' Greater Atlantic Regional Fisheries Office (GARFO, 2021). These data were used to verify simulated fishing behaviour and Atlantic surfclam catch rates (Figure 6, Munroe *et al.*, 2022), and also to assess the economic parameterizations used in this analysis. The vessel decision heuristic employed in the model was based on expectations regarding catch rates and trip duration and, therefore, the economic parameterization described below did not influence model behaviour but rather acted to scale model outputs.

Fleet revenues

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

$$R_{i,t} = Cages_{i,t}\ \ CagePrice, \tag{1}$$

where $Cages_{i,t}$ is the number of cages of Atlantic surfclams landed by fishing vessel i at time t obtained from the simulations that included fishing, as described in Munroe *et al.* (2022). The ex-vessel price per cage landed (*CagePrice*) was based on average annual bushel prices from 2017 to 2019 obtained from the 2020 stock assessment report (NEFSC, 2022) and using the industry conversion of 32 bushels (1 bushel = 53.2 l) per standard cage (i.e. 1.7 m^3). The gross domestic product (GDP) implicit price deflator (US BEA, 2021) was used to adjust prices for 2017 and 2018 to 2019 dollars. The parameter *CagePrice* was set equal to the 3-year landings-weighted average price of USD 458.75 $\mathrm{cage^{-1}}$ (2019 dollars). Atlantic surfclam ex-vessel prices are highly inelastic since the majority of processed product is purchased by a small number of large consumer goods companies that can easily substitute imported clams (Mitchell *et al.*, 2011; Northern Economics, 2019). Thus, a fixed price was used for all simulations.

Fleet costs

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

$$C_{i,t}^{share} = \ fr\ R_{i,t}, \tag{2}$$

$$C_{i,t}^{fuel} = FuelPrice_p \times \left(Hr_{i,t}^{steam}\ FuelSteam_i + Hr_{i,t}^{fish}\ FuelFish_i\right), \tag{3}$$

$$C_{i,t}^{maint} = (MjrMnt_t\ \ TSurf_i) + (RegMnt_i\ NTrip_{i,t}), \tag{4}$$

$$C_{i,t}^{insur} = \left(HulIns_{i,t} + (PIIns_t\ NCrew_i) + OtherIns_t\right) \times TSurf_i, \tag{5}$$

$$C_{i,t}^{quota} = Cages_{i,t}\ QuotaPrice. \tag{6}$$

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

$$TC_{i,t} = C_{i,t}^{share} + C_{i,t}^{fuel} + C_{i,t}^{maint} + C_{i,t}^{insur} + C_{i,t}^{quota}. \tag{7}$$

Crew and captain share costs for vessel, i, at time, t [Equation (2)] were specified as a fixed fraction, fr, of gross revenues estimated from Equation (1). The parameter fr was set to 0.3 based on information provided by Atlantic surfclam fishing vessel captains and industry representatives. Some captains indicated payments were a fixed dollar value per bushel while others were paid as a percentage of gross revenue, e.g. 7% per crew member and 9% for the captain, with the captain share being typically 30% more than a crew share. Fixed dollar values and individual revenue shares were approximately 30%

Table 2. The number of Atlantic surfclam fishing vessels and processors associated with ports along the US east coast (port locations shown in Figure 1) as well as port-specific fuel prices and landings-weighted average distances traveled for processing. Fuel prices (2019 USD) were based on region-specific averages provided by the Energy Information Administration (EIA, 2020). Processing distance is the average distance in kilometers (km) between port of landing and associated processing plants used by the Atlantic surfclam fishing vessels landing at that port. A total of two processing companies were associated with multiple ports.

Port location	Vessels (number)	Processors (number)	Fuel price (USD l^{-1})	Processing distance (km)
New Bedford, MA	11	2	0.81	335
Point Pleasant, NJ	2	1	0.85	167
Atlantic City, NJ	18	3	0.85	129
Ocean City, MD	2	1	0.85	266

of gross revenues for a crew of three and one captain, which is standard in the Atlantic surfclam fishery. This crew share estimate is similar to that discussed in Brandt and Ding (2008), particularly when the vessel owner also owns quota used for the trip, which is common in the present Atlantic surfclam fishery given the high level of vertical integration.

Fuel consumption (l h^{-1}) while steaming, $FuelSteam_i$, and fishing, $FuelFish_i$, were provided by the Atlantic surfclam industry for each vessel included in the simulations (Table 1). Fuel consumption rates were applied to the total hours spent steaming ($Hr_{i,t}^{steam}$) and fishing ($Hr_{i,t}^{fish}$) obtained from a fishing simulation to calculate total fuel use for each simulated vessel during a particular time period. Fuel cost [Equation (3)] was then determined using fuel prices ($FuelPrice_p$) that varied by port, p (Table 2). Fuel prices were based on annual average prices for New England and Central Atlantic regions provided by the Energy Information Administration for years 2017–2019 (EIA, 2020), adjusted for inflation.

The estimated maintenance costs for each Atlantic surfclam fishing vessel [Equation (4)] included fixed annual costs for major maintenance and repair ($MjrMnt_t$), such as haul-outs for painting, engine repairs, and vessel improvement, as well as regular maintenance ($RegMnt_i$), such as gear repair. Using information provided by Atlantic surfclam fishing vessel captains and industry representatives, and financial statements for seven vessels provided by one company, major maintenance costs were estimated to be about USD 150 000 every two and a half years per vessel (USD 60 000 $year^{-1}$ and USD ~1154 $week^{-1}$). Major maintenance costs were adjusted based on the fraction of total annual trips taken by a fishing vessel that targeted Atlantic surfclams ($TSurf_i$), such that only a portion of annual haul-out costs were attributed to surfclam fishing. The proportion of total annual trips for each vessel targeting Atlantic surfclams was provided by industry representatives and verified using vessel trip report data (Table 1). Discussions with industry members, review of vessel financial statements, and evaluation of estimates cited previously in the literature (e.g. Kirkley *et al.*, 2002; Das, 2014) indicated that regular maintenance costs, $RegMnt_i$, do not vary substantially for small ($\leq$ 24 m), medium (24–29 m), or large (> 29–33 m) vessels, though might be higher for jumbo (> 33 m) vessels. Therefore, a fixed value of USD 3000 $trip^{-1}$ was used for small, medium, and large vessels while USD 5000 $trip^{-1}$ was used for jumbo vessels. These values were multiplied by the number of trips taken by a vessel during time period t, $NTrip_{i,t}$, and added to major maintenance costs to obtain total maintenance costs for vessel, i, at time, t [Equation (4)].

Insurance cost estimates were determined following captain discussions, conversations with industry representatives, and evaluation of vessel annual insurance cost statements (n = 7 vessels). Annual hull insurance for each vessel, $HulIns_{i,t}$, was approximated at USD 10 000 $year^{-1}$ for small vessels, USD 20 000 $year^{-1}$ for medium and large vessels, and USD 60 000 $year^{-1}$ for jumbo vessels. Protection and indemnity insurance, $PIIns_t$, was estimated at a rate of USD 5000 per crew member and scaled by the number of crew per vessel, $NCrew_i$ (Table 1). Additional insurance related to excess liability for crew and pollution coverage, $OtherIns_t$, was estimated to be about USD 10 000 $year^{-1}$ for each vessel, independent of vessel or crew size. The sum of the costs for hull, protection and indemnity, and additional insurance was scaled by the fraction of annual fishing trips targeting Atlantic surfclams ($TSurf_i$) as insurance is paid out annually and shared across trips targeting different species [Equation (5)].

Industry members indicated prices associated with leasing quota have varied between USD 3 $bushel^{-1}$ and USD 5 $bushel^{-1}$ over the past decade, with recent average quota lease prices closer to USD 3 $bushel^{-1}$. Although the annual quota for the fleet is generally not binding, non-zero quota prices have persisted for several years, possibly due to dynamic in-season expectations and heterogeneity in the distribution of quota ownership. This value was used as the lease price ($QuotaPrice$), that was scaled by the number of cages landed by vessel, i, at time, t, ($Cages_{i,t}$) to calculate the quota cost [Equation (6)]. Quota ownership data are publicly available, but this information is not easily linked to vessel ownership. In this analysis, quota costs represent either a realized business expense or an opportunity cost, depending on whether or not quota for a trip's landings was owned by the vessel owner. Industry members described quota costs as a key financial consideration and operational constraint. Therefore, independent of ownership, quota costs for all landings are included here in assessing vessel financial performance.

Total landings, time spent steaming and fishing, and the number of trips were calculated by vessel and year using vessel trip reports (n = 6830 trip observations from 2015 to 2019 for 33 vessels; GARFO, 2021). These fishing activity measures were then used with the economic parameterization [Equations (1)–(7)] to assess annual average costs and revenues by vessel size class (Table 3) as well as to compare cost estimates with data provided by the NEFSC's Social Sciences Branch (Supplementary Table S1). Fuel costs represented the largest expense for medium, large, and jumbo vessels, while for small vessels maintenance costs were dominant. Total costs exceeded revenues for small, medium, and large vessels and were nearly equal for jumbo vessels. Negative profit margins are reasonable here given the vertical integration in the industry and suggest that vessel operations are routinely subsidized by the processing sector. Annual cost estimates based on

Table 3. Annual cost and revenue estimates (2019 USD) for each Atlantic surfclam fishing vessel size class (small ≤ 24 m, medium 24–29 m, large > 29–33 m, and jumbo > 33 m) as mean values and standard deviations (italics). Estimates are based on Atlantic surfclam fishing activity obtained from fishing vessel trip reports and economic parameterizations developed for this analysis. The number of fishing vessels in each size class is shown.

Vessel size class	Share (USD)	Fuel (USD)	Maintenance (USD)	Insurance (USD)	Quota (USD)	Total costs (USD)	Revenues (USD)
Small ($n = 11$)	164 119	202 588	217 596	38 191	114 448	736 942	547 062
	132 105	*193 295*	*91 697*	*2428*	*92 123*	*478 888*	*440 349*
Medium ($n = 10$)	239 496	302 442	220 617	42 924	167 013	972 492	798 320
	111 523	*175 079*	*87 356*	*11 878*	*77 770*	*422 326*	*371 743*
Large ($n = 8$)	167 171	321 703	174 329	39 181	116 576	818 960	557 235
	101 080	*244 501*	*117 501*	*16 724*	*70 488*	*512 037*	*336 934*
Jumbo ($n = 4$)	489 740	511 349	219 471	70 086	341 520	1632 166	1632 466
	213 166	*248 385*	*65 984*	*25 856*	*148 651*	*662 820*	*710 552*

the parameterization presented here were similar to 2011 data collected by the NEFSC (Supplementary Table S1). The sensitivity of profit margins by vessel size class was explored with three alternative economic parameterizations: a high-cost parameterization, where fuel and insurance costs were increased by 25%; a low-cost parameterization, where quota costs were removed and maintenance costs reduced by 25%; and a high-price parameterization, where ex-vessel bushel prices were increased by 25%. Average profit margins were variable though largely negative across the range represented by these economic parameterizations (Supplementary Table S2).

Processor revenues

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

$$R^{proc}_{c,t} = \sum_{j} \sum_{i,c} Weight_{i,t} \times (1 - MeatLoss)\ ProductFrac_{c,j}\ WhsPrice_{j}, \quad (8)$$

where $Weight_{i,t}$ is landings in kilograms of usable meat weight by vessel, i, at time, t, obtained from fishing simulations. The amount of useable meat per bushel varied with Atlantic surfclam size and season (Powell *et al.*, 2015; Munroe *et al.*, 2022). A fixed fraction (*MeatLoss*) of the landed usable meat is lost during processing, which was set at 15% based on information provided by industry representatives and loss estimates contained in Barker and Merrill (1967) and Loesch (1977). The total production for each processing company consists of three product types, j, that include fresh, frozen, and canned products. The fraction of total production for each processing company of each product type ($ProductFrac_{c,j}$) was specified using information provided by company representatives. Landings information from vessel trip reports together with confidential product breakdowns for each processing company suggested that 20–25% of landings are processed as fresh products, 40–45% as frozen, and 30–35% as canned, though considerable variation existed across individual processors. The wholesale price charged for processed products after leaving the processing plant ($WhsPrice_j$) was specified based on information provided by industry members. Wholesale prices for clam products reported from the 2018 NMFS (NMFS, 2018) Annual Survey of the US Seafood Processors were around USD 2–4 kg^{-1}. These prices were reported in terms of final product weights rather than by the quantity of processed clam, making it difficult to adjust to prices in terms of Atlantic surfclam amounts. Additionally, reported prices do not distinguish between Atlantic surfclams and ocean quahogs, the latter being processed into generally lower-value products. Industry members indicated that while differences existed in product prices resulting from a variety of value-added steps in processing, little differentiation exists in final product price per kg of Atlantic surfclam used, which was typically USD 8.80–11 kg^{-1}. A fixed price of USD 9.92 kg^{-1} for all processed Atlantic surfclam products was, therefore, used to specify $WhsPrice_j$ in Equation (8). Total revenues for each processor are then the sum of revenues across product types landed by fishing vessels associated with the processing company [Equation (8)].

Processor transportation costs

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

$$C^{trans}_{c,t} = \sum_{i,c} Cages_{i,t}\ Distance_{i,c}\ FreightRate, \quad (9)$$

where $Cages_{i,t}$, is the number of cages landed by vessel, i, associated with a processing company, c, at time, t, $Distance_{i,c}$ is the distance in kilometers between the port of landing for vessel, i, and processing facilities for company, c, estimated using Google Maps (Table 2), and *FreightRate* is the estimated average freight rate in 2019 USD per kilometer per cage. A total of two companies used multiple ports and one company had multiple processing plants. For the company with multiple processing facilities, product flow from ports to plants was determined in consultation with a company representative and used to distribute $Cages_{i,t}$ across multiple plants. The value used to specify *FreightRate* was estimated from information contained in the American Transportation Research Institute's annual report (Williams and Murray, 2020) and from estimates provided by DAT Solutions, LLC, a large freight exchange service provider (DAT Solutions, 2020). The former reported an average marginal cost in the US Northeast region of USD 1.22 km^{-1}, which included fuel cost, truck payments, repair and maintenance, licenses and permits, truck tires, tolls, driver wages, and driver benefits (Williams and Murray, 2020). The rate reported by DAT Solutions, LLC was USD 0.98 km^{-1} for refrigerated trucks in the US Northeast during 2020 (DAT Solutions, 2020). For this analysis, an average freight rate of USD 1.10 km^{-1} was used. Industry members indicated a standard haul was 14 cages, implying a freight rate per cage of USD ∼0.08 km^{-1} cage^{-1}.

Table 4. Simulation scenarios implemented to assess the economic impacts of offshore wind energy development and imposed behavioural restrictions on the Atlantic surfclam fishery.

Scenario	Wind energy development	Behavioural restrictions
W00	None/status quo	None
W1T	Existing lease areas	No fishing, transit allowed
W1N	Existing lease areas	No fishing nor transit
W2T	Existing lease areas + future development	No fishing, transit allowed
W2N	Existing lease areas + future development	No fishing nor transit

Simulation design

The development of offshore wind energy in the MAB is expected to impact the Atlantic surfclam fishing industry, with potential effects including shifts in the number of trips taken, fishing locations, and transit routes. Economic impacts associated with exclusion and spatial displacement of the fishing fleet were assessed using a series of simulation scenarios that imposed restrictions on fishing and vessel transiting within existing wind energy lease areas as well as areas of anticipated future development (Table 4). Areas of potential future development were previously identified by the Bureau of Ocean Energy Management (BOEM) as suitable areas that may be considered for future leasing (BOEM, 2020). The simulation scenario with no wind energy development, and therefore, no restrictions on fishing or transit activity (W00; Table 4), provided a baseline for assessing the effects of restricted fishing and transit within existing leases (W1T and W1N; Table 4) and existing together with future lease areas (W2T and W2N; Table 4). For simulations with imposed behavioural restrictions related to wind development, a model grid cell was considered within a wind energy lease area if the polygons defining the lease area or potential future development area, including a 2-NM (~3.7 km) buffer, overlapped with 50% or more of a model grid cell (Figure 1, orange shaded cells). Scenarios that included potential future development (W2T and W2N) increased the spatial footprint of offshore wind in the model by ~106%, effectively doubling the area with imposed behavioural restrictions.

Simulation implementation

A total of five scenarios were simulated to assess economic conditions of the Atlantic surfclam fishery with and without constraints imposed by the placement of wind arrays (Table 4). Each scenario consisted of a set of 200 simulations. Each simulation included 33 vessels in the Atlantic surfclam fishing fleet with each vessel having a randomly assigned captain type based on one of 12 configurations. Captain types varied in searching behaviour and how expectations of catch rates in different fishing locations were formed (see Munroe *et al.*, 2022). Randomly assigning vessel-captain pairs introduced variability in decision making and fishing behaviour across simulations to capture the range observed in the existing fleet. Each simulation was run for 300 years, with no fishing during the first 100 years to allow the Atlantic surfclam population dynamics to stabilize. Fishing was enabled in the second 100 years of the simulation but without any wind-related restrictions to allow the Atlantic surfclam population to come into equilibrium with the current level of fishing mortality. The restrictions associated with the presence of offshore wind energy arrays were imposed on fishing and fishing vessel operations in the last 100 years of a simulation. Simulations without wind farms continued without restrictions on fishing or vessel operations during the last 100 years. The number of trips, total time in hours spent steaming and fishing, and landings in cages and kilograms by week for each vessel during the last 50 years of a simulation (years 251–300) were used to assess economic impacts of wind energy scenarios on the Atlantic surfclam fishery. In the last 50 years of the simulations, the Atlantic surfclam population biomass was adjusted to constant fishing pressure and the associated random variability introduced by weather restrictions, captain fishing location choices, and recruitment variability, and therefore, provided stable realizations of annual fishing activity. The 50 years of the simulation used for analyses do not provide impact projections extending 50 years into the future following construction of offshore wind farms, which would exceed the planned life of current wind turbine technology. Rather, the 50-year window used for simulation analysis yields a large set of annual impact estimates that provide information on short-to medium-term effects (e.g. occurring one to several years following construction).

Each set of simulations within a particular scenario yielded 17 160 000 weekly fishing vessel-level observations, which were aggregated to 330 000 annual vessel-level observations and 10 000 annual fleet-level observations. The total number of fishing trips, average time at sea per trip, average time fishing per trip, and average LPUE (cages per hour fishing) were used to assess changes in fishing activity corresponding to changes in behavioural restrictions across the scenarios. Annual measures of fishing fleet revenues and costs and processor revenues were used to measure aggregate economic impacts. Additionally, given that the Atlantic surfclam industry is thought to have modest profit margins, and therefore, small shifts in operating costs could reduce economic viability, economic impacts were further explored by analyzing average fleet total costs (USD cage^{-1}), average fleet fuel costs (USD cage^{-1}), and average processor transportation costs (USD cage^{-1}). Average fleet total costs were estimated by summing total costs for the simulated fishing fleet during 1 year and then dividing by the total number of Atlantic surfclam cages landed in that year. Average fleet fuel costs and average processor transportation costs were calculated similarly. Costs related to transporting product from landing sites to processing facilities were explored given the possibility of differential impacts on fishing behaviour across ports coupled with differences in distances to processing infrastructure (Table 2). Analyses of simulated changes in fishing activity and economic measures in response to the development of offshore wind energy focus on the direction of change and approximate magnitude.

Assessment of the fishing simulations using a range of fishery independent and fishery dependent data showed that the simulated biomass distributions and fishing fleet behaviour

Table 5. Percent change (%) in annual fishing trips, average time at sea, average time fishing, and average LPUE for simulation scenarios restricting fishing (W1T and W2T) or fishing and transit (W1N and W2N) in wind energy areas. Changes were calculated relative to the reference simulation with no imposed restrictions on fishing or transit (W00).

Simulation metric: fishing activity	Simulation scenario			
	W1T	W1N	W2T	W2N
Total trips	– 3.96	– 7.42	– 11.61	– 14.57
Average time at sea	1.25	8.60	5.19	12.68
Average time fishing	– 0.47	– 2.47	1.51	– 0.09
Average LPUE	1.63	3.46	– 1.87	– 0.29

accurately represented conditions in the present fishery (see Munroe *et al.*, 2022). As an additional robustness evaluation, a set of 200 simulations were run for each model scenario under a relaxed fishing decision heuristic. The modified decision rule required a captain to stay in port when no fishing locations existed that allowed filling at least 70% of their cages within trip duration constraints, rather than 100%. It was expected that this change in decision making would lead to more fishing effort in all scenarios.

Results

Changes in fishing activity

Relative to the scenario with no fishing or transit restrictions, simulations including wind energy arrays reduced the total number of Atlantic surfclam fishing trips and increased average trip length (Table 5; see Supplementary Table S3 for mean and standard deviation values). The number of fishing trips declined by 3.96% (W1T) to 14.57% (W2N) when fishable and transitable areas were reduced. Average fishing trip length increased by 1.25% for vessels that transited, but could not fish, in existing lease areas (scenario W1T), and up to 12.68% when vessels could neither transit nor fish in existing and proposed lease areas (W2N). Average fishing time per trip and LPUE showed small decreases and increases, respectively, for simulations that considered restrictions imposed within existing leases (W1T and W1N). The inclusion of regions of proposed development (W2T and W2N) led to small increases or unchanged average fishing times per trip and small reductions in LPUE. Reductions in the number of trips and increases in average trip length were most prominent during the winter and fall (October–March; Supplementary Table S4).

The imposition of restrictions on areas accessible to fishing and transit resulted in spatial shifts in simulated fishing effort, as measured by the change in total annual hours fished per model grid cell (Figure 3). Effort and catch displacement were primarily observed in the Mid-Atlantic region, where existing and proposed lease areas overlap with key Atlantic surfclam fishing grounds off New Jersey and New York (Figure 1). When prevented from fishing in existing leases, but still allowed to transit, fishing effort was displaced offshore of the existing lease areas off New Jersey (Figure 3a). The removal of transit as well as fishing access in existing lease areas resulted in fishing effort concentrating more heavily inshore and reducing overall (Figure 3b). The inclusion of proposed wind energy leases led to reductions in effort offshore of existing lease areas and increased fishing intensity in a small inshore region off New Jersey as well as further south (Figure 3c and d). Displacement of catch closely followed displacement of fishing effort (Supplementary Figure S1). On Georges Bank (east of 69°W), fishing effort and catch exhibited small shifts westward (Figure 3 and Supplementary Figure S1). Areas east of Nantucket Island and south of Cape Cod, Massachusetts, known as Nantucket Shoals (approximately 70°W), saw a northward shift (scenarios W1T and W2T) and overall reductions in effort and catch (scenarios W1N and W2N). Across scenarios, aggregate effort and catch did not change substantially in either Georges Bank or Nantucket Shoals however. Note that portions of Nantucket Shoals are subject to closures for habitat concerns and such closures were not included in our model.

For the simulations that included the relaxed decision rule, fishing effort tended to be higher, as seen in the increased numbers of trips, average time at sea, and average time fishing across scenarios, while LPUE was lower (Supplementary Table S5). In scenarios with offshore wind development, the relaxed decision rule led to smaller reductions in the number of trips. Scenarios including proposed development areas (W2T and W2N) saw reductions in LPUE, however, indicating that while more trips were taken when the constraint keeping boats in port was relaxed, the trips were less productive.

Economic impacts

Changes in Atlantic surfclam fishing behaviour produced several economic effects, with a contraction of total fishing fleet revenues of 2.84% (scenario W1T) to 14.85% (W2N), consistent with reductions in trips taken by the fleet (Table 6; see Supplementary Table S6 for mean and standard deviation values). The reduction in fishing effort translated into reductions in operational costs, with a reduction in simulated total fleet costs of 2.78% (W1T) to 10.70% (W2N). Percentage reductions in Atlantic surfclam processor revenues mirrored reductions in fleet revenues, with minor differences due to seasonal variation in meat weight. Simulated annual revenue reductions ranged from USD 0.93M (W1T) to USD 4.84M (W2N) for landed product and USD 3.27M (W1T) to USD 17.36M for processed product (Supplementary Table S6). Average total costs and average fuel costs did not meaningfully change when Atlantic surfclam fishing was restricted in existing lease areas (W1T; Table 6). However, all other scenarios (W1N, W2T, and W2N) resulted in notable increases in average costs. In particular, scenarios restricting fishing vessel transit (W1N, W2N) produced increases in average fuel costs of 5.55% (W1N) and 9.92% (W2N), which increased average total costs of production. Average transportation costs increased in all scenarios (Table 6) as proportionally more product was landed in New Bedford, MA, following greater changes in fishing activity for the southern fleet (Figure 3; Supplementary Tables S7 and S8). The market mix of wholesale products remained consistent across model scenarios, with ~22% of landings being processed as fresh, ~43% as frozen, and ~36% as canned products (Supplementary Table S9).

Port-specific Atlantic surfclam fishing activity and economic measures showed regional differences, with negative effects of offshore wind development largely concentrated in Atlantic City, NJ (Supplementary Tables S7, S8, S10, and S11; Figure 4). For Atlantic surfclam fishing vessels with a homeport in Atlantic City, NJ, introducing fishing and tran-

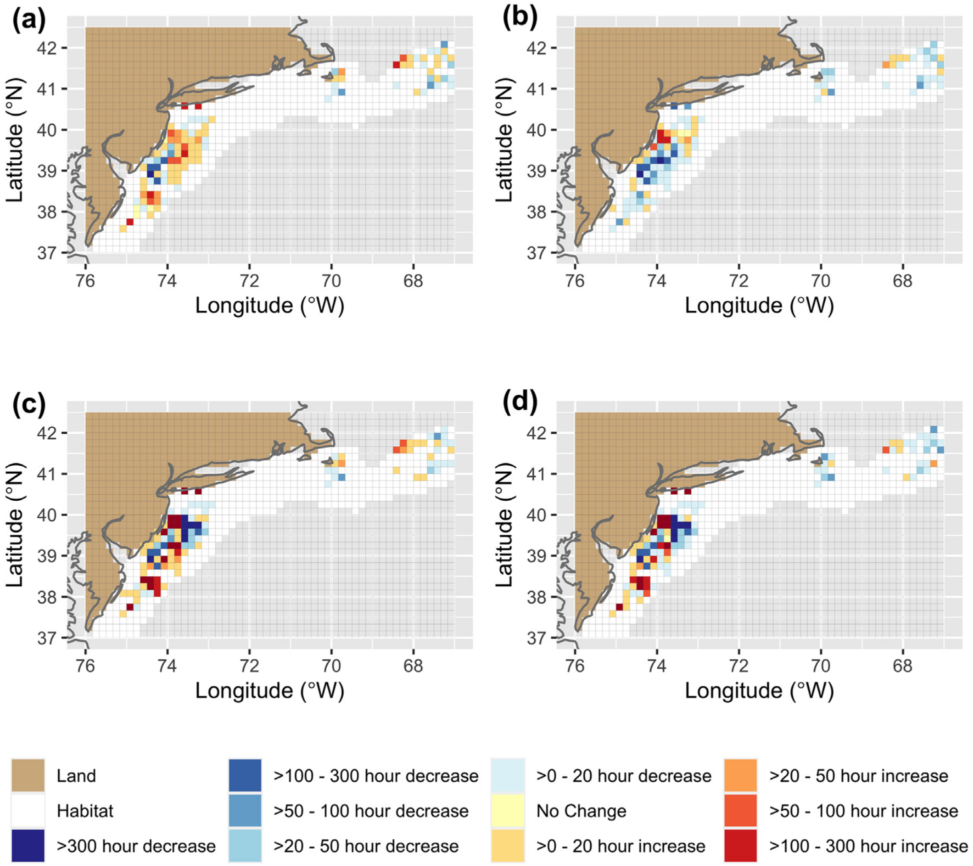

Figure 3. Simulated Atlantic surfclam fishing effort displacement, indicated by the change in the average number of hours fished per model grid cell per year, for scenarios that allow (a) transit but no fishing in existing lease areas (W1T), (b) neither transit nor fishing in existing lease areas (W1N), (c) transit but no fishing in existing and proposed lease areas (W2T), and (d) neither transit nor fishing in existing and proposed lease areas (W2N). Fishing effort displacement in each model grid cell was calculated for each simulation scenario relative to the average annual hours fished in that grid cell with no transit or fishing restrictions (W00). A decrease (increase) in average effort for a model grid cell under a particular scenario indicates behavioural restrictions led to less (more) time fishing in that area.

Table 6. Percent change (%) in total annual revenues and costs for the Atlantic surfclam fishing fleet, total annual revenues for processors, average fleet total costs, average fleet fuel costs, and average processor transportation costs for simulation scenarios that restricted fishing (W1T and W2T) or fishing and transit (W1N and W2N) in wind energy areas. Changes were calculated relative to the reference simulation with no imposed restrictions on fishing or transit behaviour (W00).

Simulation metric: economic outcomes	Simulation scenario			
	W1T	W1N	W2T	W2N
Total revenues (fleet)	– 2.84	– 6.53	– 11.92	– 14.85
Total costs (fleet)	– 2.78	– 4.38	– 9.37	– 10.70
Total revenues (processors)	– 2.88	– 6.62	– 12.30	– 15.31
Average total costs (fleet)	0.07	2.34	2.92	4.93
Average fuel costs (fleet)	– 0.06	5.55	4.93	9.92
Average transportation costs (processors)	0.76	1.25	3.26	4.09

sit restrictions in wind energy areas led to reductions in simulated fishing trips from 5.46% (W1T; Supplementary Table S7) to 20.54% (W2N) and increases in average time at sea from 0.77% (W1T) to 14.70% (W2N). Additionally, scenarios including restrictions in areas of potential future development resulted in reductions in LPUE for Atlantic City, NJ fishing vessels of 7.44% (W2T) and 6.44% (W2N). Simulated revenues for the Atlantic City, NJ fishing fleet and associated processors decreased by ~5% (W1T) to over 25% (W2N; Supplementary Table S10). Average total costs and average fuel costs for these vessels also increased across all scenarios. The simulated fleet with New Bedford, MA as its homeport was mostly unaffected by lease area restrictions, although simulations imposing restricted transit within the wind energy lease areas (W1N and W2N) showed increased time at sea and average fuel costs (Supplementary Tables S8 and S11).

Simulations using the relaxed fishing decision rule resulted in increased fishing effort and, therefore, increased revenues and total costs across scenarios (Supplementary Table S12). Average total costs and average fuel costs were also higher across scenarios, given trips averaged lower LPUE with the

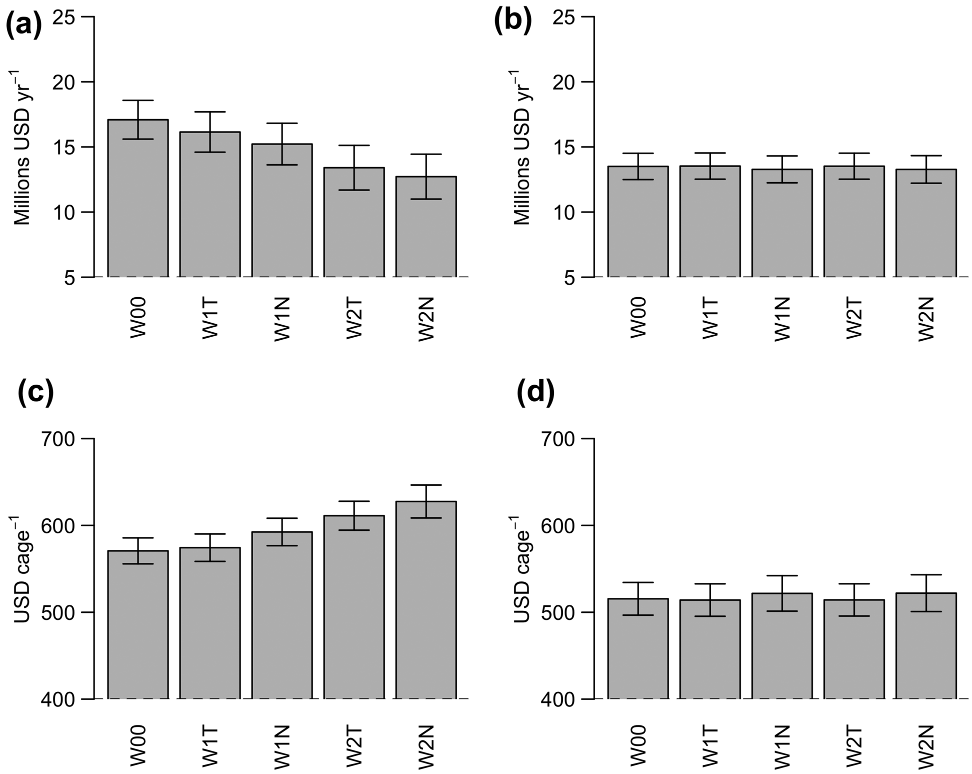

Figure 4. Simulated economic metrics calculated for each simulation scenario (see Table 4) for Atlantic surfclam fishing vessels landing in Atlantic City, NJ (left panels) and New Bedford, MA (right panels) showing, (a) and (b) total annual fleet revenues, and (c) and (d) average total costs. Values shown are means taken across 10 000 observations from the last 50 years of simulations for a particular scenario. Error bars indicate one standard deviation.

relaxed constraint. Scenarios including offshore wind energy development saw total fleet revenues reduce by 1.19% (W1T) to 8.30% (W2N) while average total costs increased from 0.33% (W1T) to 5.36% (W2N) and average fuel costs increased from 0.87% (W1T) to 12.28% (W2N). In simulations with the relaxed decision rule, revenue reductions from offshore wind energy development were attenuated although fishing cost increases were intensified. Profit margins for the fishing fleet were lower (larger negative values) and decreased more substantially in response to offshore wind energy development under the relaxed decision rule (Supplementary Figure S2), indicating that increased flexibility in trip taking behaviour would not mitigate negative economic impacts to the Atlantic surfclam fleet.

Discussion

Surfclam industry impacts

Imposing exclusionary restrictions on Atlantic surfclam vessel fishing and transit in wind energy areas increased fishing trip travel time and total time at sea, leading to reductions in the number of trips taken by the fleet and increased costs associated with displaced fishing effort. The current fleet fishes year-round, with boats frequently making one to two trips per week. Increased travel time reduced the number of opportunities available for fishing trips, leading to reduced landings revenues as well as increased average production costs. Additionally, excluding vessels from offshore wind energy areas displaced effort to grounds that were too far to fish within trip duration constraints, or to areas that have lower rates of catch and, thus cannot be fished as efficiently. Simulations that used the relaxed fishing trip decision heuristic increased the number of high-cost trips that were taken, reducing revenue losses though amplifying cost increases arising from offshore wind energy development. This analysis suggests that fishery exclusion and fishing effort displacement resulting from development of offshore wind energy resources along the US Northeast and Mid-Atlantic continental shelf are likely to adversely affect the profitability of the Atlantic surfclam fishing industry.

While the magnitude of impacts differed across development scenarios, all showed reductions in fishing activity. The present Atlantic surfclam fleet directly employs ~130 individuals as crew (Table 1) and additionally supports many jobs in processing plants and ancillary industries. In 2018, commercial fisheries in Mid-Atlantic states produced nearly USD 500 million in annual landings with total economic impacts of USD 1.8 billion that supported over 25 000 jobs (NMFS, 2021). Using the National Renewable Energy Laboratory's Jobs and Economic Development Impact model for offshore wind, Tegen *et al.* (2015) estimated that operations and maintenance activities associated with a moderate level of offshore wind development in the Mid-Atlantic by 2030 would, similarly, support nearly USD 2 billion in annual economic activity and around 9500 jobs, including 680 jobs in project development and onsite labor. Presently, many of the tradeoffs and interactions between the commercial fishing and offshore wind energy sectors are unclear, and much work remains to identify and promote potential synergies and co-benefits (Hooper *et al.*, 2018; Schupp *et al.*, 2019; Haggett *et al.*, 2020; Methratta *et al.*, 2020). Nevertheless, this analysis suggests that the development of offshore wind may come with costs in terms of reductions in landings and fishing activity for certain com-

mercially exploited species, with impacts to dependent fishing communities largely unknown.

Seafood processing is an important source of employment and frequently a primary driver of profit generation for many coastal communities around the world (Anderson *et al.*, 2015). The processing sector is rarely considered when evaluating impacts of policy or changes in fisheries management, however, largely due to data limitations (Guldin and Anderson, 2018). For this analysis, the vertical integration of the Atlantic surfclam industry required consideration of the processing sector in assessing economic effects resulting from changes in fishing activity due to offshore wind energy development. Changes in processor revenues were found to closely follow changes in fishing fleet revenues due to consistent markups across product types. Additionally, the market mix of wholesale products remained constant across simulation scenarios, despite heterogeneous impacts across regions and processors. Offshore wind energy development was found to influence average transportation costs given that changes in fishing activity for the simulated fishing fleet varied across ports and travel distances for landed product were port and processor specific. While other costs faced by processors were not considered in this analysis, reductions in landed Atlantic surfclam volumes could increase average processing costs in the presence of large fixed costs (e.g. costs associated with processing facilities and specialized equipment).

A consistent result across the simulation scenarios was that fishing costs exceeded revenues, indicating that the fishing fleet was unprofitable. Profitability across Atlantic surfclam fishing vessel size classes has been documented previously (e.g. MAFMC, 1986). However, recent analyses have noted the industry's small profit margins and indicated that the fishery's annual quota is not regularly caught likely due to exogenous constraints on demand and increasing prices for key inputs (Mitchell *et al.*, 2011; Northern Economics, 2019). The captain's decision-making approach used to determine behaviour of simulated fishing vessels was based on expected catch rates, travel distances, and constraints on time at sea, rather than anticipated profitability. This heuristic reflects how fishing decisions are presently made and, therefore, provides a plausible forecast of fishing behaviour following the development of offshore wind. Over a longer time period, vertically integrated Atlantic surfclam companies should be expected to adjust fishing effort and locations, quota holdings, product transport, and processing operations to optimize profits. This level of analysis was beyond the scope of this study, but points to the need for increased consideration of industry structure, organization, and their impacts on agent decision-making in future implementations of integrated bioeconomic models.

This analysis used fixed ex-vessel and wholesale prices to estimate fleet and processor revenues. It has been suggested that reported ex-vessel prices may not correspond to market conditions since Atlantic surfclam fishing vessels are mostly controlled or owned by the processing sector (Walden *et al.*, 2012). Incorporating a demand model, wherein prices respond to shifts in landed quantities, would increase revenues under simulation scenarios with reduced landings, potentially improving fleet profitability and partially compensating for losses arising due to harvest reductions and increased fishing costs. Available data and information on market structure indicated that Atlantic surfclam prices are inelastic (e.g. Mitchell *et al.*, 2011; Northern Economics, 2019). However, it is possible that large reductions in landed Atlantic surfclam volume resulting from fishery exclusion and displacement could elicit a price response.

Atlantic surfclam vessels and processors participate to varying degrees in the ocean quahog fishery. Lipton and Strand (1992) estimated cost functions for vessels targeting Atlantic surfclams and ocean quahogs to evaluate optimal industry structure for different regulatory regimes. Their analysis showed that under both open access and optimal profit-maximizing management the fishing fleet would be composed of exclusively multiproduct firms, implying that management decisions in the Atlantic surfclam fishery should consider feedbacks across both species (Lipton and Strand, 1992). Weninger and Strand (2003), meanwhile, found diseconomies of scope in multiproduct production and indicated that participation in both Atlantic surfclam and ocean quahog fisheries is most likely the result of effort restrictions in the Atlantic surfclam fishery and is not an economically efficient behaviour. For the fleet analyzed here, about one-third of Atlantic surfclam fishing vessels also targeted ocean quahogs. This analysis did not consider behavioural responses across multiple target species, which could influence fleet dynamics. It is not expected, however, that effort in the ocean quahog fishery would appreciably expand to offset impacts on the Atlantic surfclam fleet caused by offshore wind development. Ocean quahog is considered a low-value target with limited ability to substitute for landings of Atlantic surfclam, which are generally processed into higher value products. The fishery faces similar exogenous demand constraints to Atlantic surfclam, with annual landings regularly under quota, suggesting current levels of exploitation are the most the market can bear. Additionally, overlap between ocean quahog fishing grounds and potential wind energy development areas has been noted previously (Kirkpatrick *et al.*, 2017) and may constrain future fishing activity. Atlantic surfclam and ocean quahog vessels utilize specialized gear, limiting the ability for operations to shift into targeting other species in response to offshore wind development. Further analysis is needed to quantify potential market, regulatory, and environmental interactions occurring between US Atlantic clam fisheries that could influence long-term industry change arising from offshore wind development.

Commercial fisheries and wind energy

Economic impacts to commercial fisheries from offshore wind energy development depend on responses to operational constraints imposed on commercial fishing vessels, which are largely unknown for the US fleet. Atlantic surfclam vessels that attempt to fish in a developed wind lease area, that includes support structures, rock reinforcements, and power cables buried in the seabed, will need to operate within restricted lanes or in ways that may be less efficient than if unrestricted in the length and direction of tows. For example, an Atlantic surfclam fishing vessel attempting to fish within a wind farm would likely need to haul back more frequently to avoid cables and other infrastructure. These operational responses may reduce fishing efficiency, force fishing vessels to return to port with less than full loads, and potentially impact catch transport and processing. In Europe, where offshore wind energy development has been steadily increasing over the last two decades, use of mobile gear within wind arrays is generally restricted or extremely limited (Gill *et al.*, 2020) and several barriers are thought to remain to compatible ocean multi-use (Gusatu *et al.*, 2020; Schupp *et al.*, 2021). Additional research

is needed to more fully explore the interactions of fishing within lease areas and the resulting economic impacts, though for the Atlantic surfclam fleet, this mode of operation is not anticipated.

The placement, design, and spatial extent of offshore wind energy infrastructure are expected to influence vessel transit and fishing behaviour (Gray *et al.*, 2016; Methratta *et al.*, 2020). The simulations described here showed that increases in the spatial footprint of offshore wind energy presence generally caused disproportionate increases in economic impacts. This suggests that economic effects may respond non-linearly to increases in the extent of offshore wind development due to cumulative impacts as well as the relative importance of different sites. Commercial fishers in the United States have expressed concerns related to increased vessel congestion, navigational challenges, and risks of collision or allision in relation to proposed offshore wind development (Hall and Lazarus, 2015; ten Brink and Dalton, 2018). Additionally, fishing trip decisions have been found to be influenced by weather, given changes in risk associated with travel and operation of fishing gear (Pfeifer, 2020). The scenarios evaluated in this analysis showed that the largest economic impacts to the Atlantic surfclam fishery were the result of restrictions in transit behaviour. Further exploration is needed to better understand the effects of alternative turbine spacing, inclusion of transit corridors, and weather-dependent vessel behaviour.

Conclusions

The changes in revenues and costs for the Atlantic surfclam industry estimated here should be considered short- to medium-term effects. Over the longer-term, it is likely that the Atlantic surfclam industry will adjust to new conditions, adapting to maximize profits with added constraints on fishing behaviour related to development of offshore wind energy or failing to continue operations. Warming waters throughout the MAB have caused a northward shift in range for the Atlantic surfclam over the last several decades (Hennen *et al.*, 2018; Hofmann *et al.*, 2018), reducing catch per unit effort for the southern and inshore portions of the stock and ultimately resulting in a northward movement of processing capital and fishing vessels (McCay *et al.*, 2011; Powell *et al.*, 2015). This economic analysis indicates that the effects of offshore wind energy development will disproportionately impact Atlantic surfclam fishing activity in the Mid-Atlantic, where the areas designated for development overlap with existing fishing grounds or are used in transiting to and from fishing areas. Offshore wind energy development may, therefore, act as an added stressor for this portion of the industry, exacerbating and accelerating reductions in profitability. Future research integrating environmentally-dependent resource dynamics with spatially explicit models of fishing and processing activity are needed to more fully understand the potential interactive and cumulative effects of climate change and offshore wind energy development on commercial fishing industries across the US Northeast and Mid-Atlantic.

Increasing or anticipated overlap and interaction between traditional ocean uses, such as fisheries and shipping, and new economic sectors, such as aquaculture, renewable energy production, and seabed mining, have motivated the need to understand and effectively manage multi-use ocean settings (Klinger *et al.*, 2018; Schupp *et al.*, 2019). Critical to the capacity to consider and evaluate use conflicts and alternative development scenarios is the ability to quantitatively assess cross-sector interactions and tradeoffs among competing ocean uses (Burgess *et al.*, 2018). The analyses presented here assess output from an agent-based bioeconomic model that allows comparisons of simulations of the existing Atlantic surfclam fishery with those from counterfactual scenarios introducing spatially-dependent vessel behavioural restrictions. Other methods have been used to evaluate the economic impacts of spatial management, such as the random utility approach used to quantify welfare effects of essential fish habitat closures in the Atlantic surfclam fishery (Hicks *et al.*, 2004). These methods often rely on econometric models of fishing location choice and produce counterfactual scenarios by modifying the set of available fishing locations under alternative policies (e.g. Haynie and Layton, 2010). The development of offshore wind will result in novel decision-making conditions, complicating the ability to forecast fishing behaviour. Significant opportunity exists for these different approaches to be used complimentarily, such as in model calibration (e.g. Carrella *et al.*, 2020) and in validating impact estimates. Spatially resolved bioeconomic agent-based models are an underutilized tool in fisheries modelling and economic analyses (Burgess *et al.*, 2020) though offer substantial capacity to explore interactions between offshore wind and commercial fisheries, as demonstrated here.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

The data used in this research associated with individual vessel behaviour and characteristics cannot be shared publicly because it is considered private and confidential information. Summary data not included with the article or associated supplementary materials will be shared upon reasonable request to the corresponding author.

Authors' contributions

AMS, DMM, ENP, EEH, and JMK conceived ideas and acquired funding; all authors developed the methodology and contributed to the model calibration and validation; JMK wrote and maintained the *SEFES* model code; AMS and JB conducted the economic analyses of the model output; AMS drafted the initial manuscript; all authors contributed to the manuscript review and editing.

Acknowledgements

We are immensely grateful to the Atlantic surfclam fishing industry and management representatives for volunteering their time and knowledge of the fishery throughout all phases of this project. We also thank the many captains of the Atlantic surfclam fishing vessels who discussed their livelihood with us and ensured our model was reflective of their experiences and decision-making processes. We thank two reviewers who provided constructive comments that greatly improved this manuscript. Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management, Environmental Studies Program, Wash-

ington DC, under contract number M19AC00016. This paper is Contribution No. 4100 of the Virginia Institute of Marine Science, William & Mary.

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Handling Editor: David Secor