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Impacts of offshore wind energy development on the commercial sea scallop fishery

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ABSTRACT

The Atlantic sea scallop (*Placopecten magellanicus*) fishery on the Northeast U.S. continental shelf generates approximately USD 500 million ex-vessel revenues annually, making it one of the most valuable single species fisheries in the United States. Wind energy development is planned for key areas on the U.S. Mid-Atlantic shelf where the Atlantic sea scallop fishery operates, creating novel challenges in managing trade-offs between traditional users like fisheries and new users like offshore wind energy. An agent-based modeling framework that integrates spatial dynamics in Atlantic sea scallop stock biology, fishing fleet behavior, and federal management decisions, was implemented to investigate how offshore wind energy infrastructure may directly affect the Atlantic sea scallop fishery. The effect of current and planned wind energy lease areas on Atlantic sea scallop was evaluated with simulations that restricted Atlantic sea scallop fishing in lease areas, transiting lease areas by the fishing fleet, or both. The relative effects of these restrictions were measured against a simulation without any restrictions.

Simulations indicated that wind energy lease areas have minor impacts on the present-day fishery, with changes in days fished, landings per unit effort, and total fishing trips under 5% with impacts varying across development scenarios and fishing ports. These results suggest offshore wind development may have limited impacts on fishing. However, these changes can be magnified by the value of the Atlantic sea scallop fishery, resulting in substantial economic impacts. Imposed restrictions on fishing location and transiting lease areas resulted in spatial shifts in fishing trips, with larger changes associated with the larger proposed wind lease area footprints, particularly in the southern part of the Atlantic sea scallop range. The largest negative effect of wind restrictions was the reduction in Atlantic sea scallop biomass outside of the lease areas (~4–9%), likely due to effort displacement, even though the total stock biomass remained relatively unchanged. The simulation results highlight the need for a holistic approach to assessing the complex interactions between offshore wind energy lease areas, Atlantic sea scallop stock dynamics, and fishing vessel transit routes to accurately identify and address potential impacts. This information is critical for fishers and managers to assess mitigation approaches and serves as a valuable tool for future planning amid interactions between commercial fisheries, the offshore wind energy industry, and changing environmental conditions.

1. Introduction

The Northwest Atlantic, a vital region for commercial and recreational fisheries, is designated as a key area for U.S. blue-water energy production. The magnitude of offshore wind energy development planned for this region will have significant potential for economic disruption to other users of the continental shelf as well as the potential for new and unknown environmental impacts. The planned build-out of large-scale wind turbine arrays for the U.S. Northeast continental shelf region will cover over 9,310 km^2 (2.3 million acres), with 25 proposed projects to be developed by 2030 and several new lease sales forthcoming (Methratta et al., 2023). However, this planned development has faced some resistance, leading to delays (White House, 2025). The extensive spatial footprint of offshore wind energy development threatens to dislocate fishing effort and modify offshore habitat by adding hundreds of hectares of hard structure around turbine foundations and cabling (Gill et al., 2020; Methratta et al., 2020; Borsetti et al., 2023).

Commercial fisheries operating from New England and Mid-Atlantic ports generate over USD 2 billion per year in landings revenues, or about 32% of the national total revenues (NMFS, 2024). Strong cultural and economic ties to the fishing industry are present in communities throughout the area (McCay and Cieri, 2000; Jepson and Colburn, 2013; Colburn et al., 2016). The seafood industry in the New England and the Mid-Atlantic regions is estimated to directly or indirectly support nearly 435,000 jobs with total sales impacts of over USD 61 billion annually

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(NMFS, 2024). Commercial fisheries for bivalve shellfish species are key economic drivers and include a large fishery for Atlantic sea scallop (*Placopecten magellanicus*), the third highest value U.S. single-species fishery worth approximately USD 500 million annually (NMFS, 2022a).

Bivalve shellfish are expected to be the most impacted fisheries by offshore wind energy development because of the fishing gear type used (bottom dredge) and stationary stock distribution (Kirkpatrick et al., 2017). Fishery exclusion and displacement arising from offshore wind energy development is estimated to reduce future revenues in the Atlantic surfclam (*Spisula solidissima*) fishery by 3–15%, with reductions as large as 25% for certain fishing ports (Scheld et al., 2022). An assessment of the potential impact of past fishing activities on exposure to the Atlantic sea scallop fishery found that up to 6% of the fishing trips could be affected by offshore wind energy development Chaji et al. (2024). Offshore wind energy development is also expected to impact up to fourteen federal stock assessment surveys (Methratta et al., 2023), as well as non-federal surveys (e.g., Scallop Research Set Aside surveys, Northeast Area Monitoring and Assessment Program surveys), thereby increasing uncertainty in estimation of biological reference points and complicating management decisions (e.g., Borsetti et al., 2023). These potential short-term changes are occurring in tandem with longer-term climate-driven shifts in oceanographic conditions on the U.S. Northeast continental shelf (Saba et al., 2016; Friedland et al., 2020). As a result, future stock biomass, abundances, and distribution, as well as commercial fishing and its management, depend on the individual and interactive effects of natural and anthropogenic environmental changes.

The complex interactions between wind farm arrays, stock biology, fishers' decision-making, stock assessments and fisheries management must be considered to fully address potential impacts of offshore wind energy development on fisheries. Comprehensive fishery models, also referred to as integrated ecological–economic fisheries models (Nielsen et al., 2018), provide tools that can be used to investigate complex interactions among biology, ecology, management, and socioeconomics to develop guidance for sustainable and cogent marine spatial planning decisions. Few integrated modeling tools are presently available that enable projection of fishery resource and fishing industry dynamics in the context of competing ocean uses. Such modeling tools are, nonetheless, important for identifying adaptation strategies that reduce economic dislocation of commercial fisheries, improve management coordination and effectiveness, and sustainability of socio-ecological fishery systems (de Groot et al., 2014; Willis-Norton et al., 2024). This approach is particularly useful when considering system behavior that is non-linear or exhibits thresholds, characterized by temporal correlation, or subject to stochastic processes (Bonabeau, 2002).

The objective of this study was to examine potential fishery impacts resulting from spatial displacement and exclusions of the Atlantic sea scallop fishery arising under different offshore wind energy development scenarios. This objective was addressed using an integrated modeling framework based on an agent-based model, the Spatially Explicit Fishery Economics Simulator (SEFES), that was originallydeveloped for the Atlantic sea scallop fishery. Implementations of SEFES assessed interactions between Atlantic sea scallop population dynamics and fishing fleet behavior and the effects of different wind energy development scenarios on the Atlantic sea scallop fishery. The simulation results provide guidance for approaches for mitigating interactions between commercial fisheries, the growing offshore wind energy industry, and changing environmental conditions.

2. Methods

2.1. SEFES model overview

The SEFES model, originally developed to simulate the dynamics of the Atlantic surfclam fishery, has been 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). More recently, this model has been updated and expanded to examine the potential economic impacts and management impacts of wind farm placement on the Atlantic surfclam fishery (Munroe et al., 2022; Scheld et al., 2022; Borsetti et al., 2023), and to estimate future Atlantic surfclam stock abundance and distribution and range shifts in response to changing environmental conditions, and future fishery displacement due to offshore wind energy development (Moya et al., 2024; Spencer et al., 2024a, 2024b).

The SEFES framework was implemented in a model domain that extends from offshore of Massachusetts southward along the continental shelf to the region offshore of Virginia (Fig. 1). The domain was divided into 10-minute squares measuring 10 min of latitude by 10 min of longitude. The model grid used is consistent with Atlantic sea scallop stock assessment survey areas and includes the home fishing ports for the Atlantic sea scallop commercial fleet (Fig. 1). The 10-min squares with an average depth between 30 m and 100 m provide biological habitat for the Atlantic sea scallop. The model domain includes fishery management access area boundaries based on the Atlantic sea scallop fishing year 2021 under Framework 33 (NEFMC, 2021).

The SEFES framework was adapted to include population dynamics, fishing fleet characteristics, fishery management areas, and fishing behavior appropriate for the biology and fishing fleet for the Atlantic sea scallop (Fig. 2). The structure used for the Atlantic sea scallop SEFES implementation is based on guidance and inputs from the Atlantic sea scallop industry and management representatives.

The total biomass and the exploitable biomass of post settlement Atlantic sea scallops, is produced by the population dynamics model that includes parameterizations based on observations for recruitment, growth, and natural and fishery-based mortality. The simulated recruitment of Atlantic sea scallops occurs annually in the fall, which represents the major spawn observed in the Atlantic sea scallop population (DuPaul et al., 1989; Davies et al., 2014), and recruits are uniformly distributed over the model domain. Recruitment is estimated using a standard Beverton-Holt stock recruit relationship (Beverton and Holt, 1993). Within each 10-min square, the number of Atlantic sea scallops per square meter is estimated at 10-mm intervals for size classes

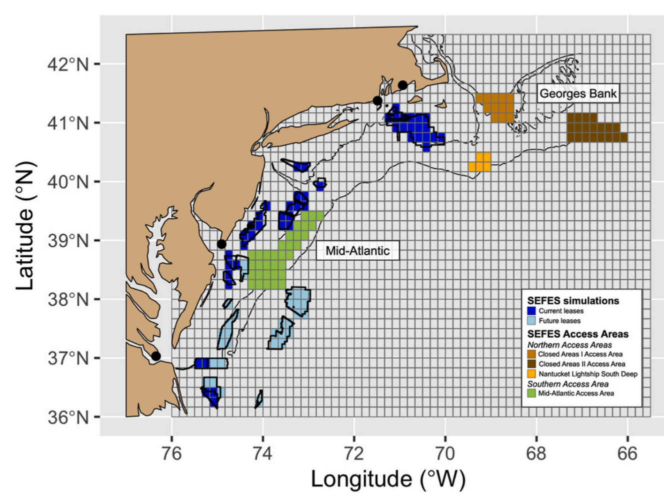

Fig. 1. Map of the Mid-Atlantic continental shelf, including Georges Bank, showing the SEFES model domain grid of 10-min squares and existing (dark blue) and potential future (light blue) offshore wind energy leases areas. Model grid cells with fishing vessel operational restrictions (blue) and fishery management access areas (oranges and green), based on access areas from 2020 to 2021 fishing years, are shown. Port landing locations for the Atlantic sea scallop fishing vessels included in SEFES are indicated (black circles) and include, from north to south: New Bedford, MA; Port Judith, RI; Cape May, NJ; and Hampton, VA. The Hampton, VA fishing port (white circle), located west of the SEFES model grid, was shifted to the nearest 10-min square (black circle). The 50-m and 100-m isobaths are shown (black lines).

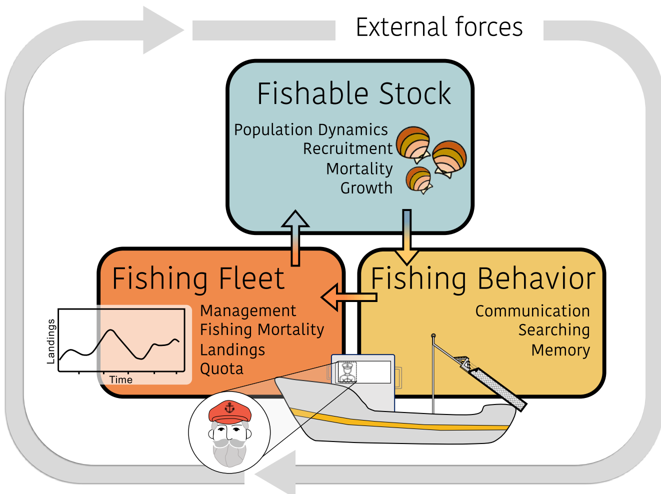

Fig. 2. Schematic of the Spatially Explicit Fisheries Economics Simulator (SEFES) showing the interactions among Fishable Stock (light blue), Fishing Behavior (yellow), and the Fishing Fleet (orange). The primary processes that operate on each component are listed. Links between components are indicated as are the external forces that affect all the model components.

from 0 to 200 mm in shell length. A simulated resource assessment survey occurs annually on November 1 and is based on 1-hour tows in all 10-min squares that represent Atlantic sea scallop habitat (Fig. 1). The catch histories for all fishing vessels in the simulated fishing fleet are updated based on the results from the annual simulated survey.

Fishing for Atlantic sea scallops is based on the approach used for Atlantic surfclams (Munroe et al., 2022). Fishing removal and efficiency are dependent on the level of communication among Captains of fishing vessels and the willingness of Captains to share information. The ability of a Captain to effectively search for fishable regions and the Captain's memory of previous fishing trips also influence fishing for Atlantic sea scallops. The fishing fleet is based on a subset of vessels currently in the Atlantic sea scallop fleet, specifically those operating under limited access permits, which represent approximately 95% of the fleet's total landings. The over 300-vessel limited access sea scallop fleet, distributed across four representative home ports (Fig. 1), was simulated to provide spatial variability in the distribution of fishing effort.

2.2. *Fishable Stock*

Atlantic sea scallop biomass (*Fishable Stock*) was obtained with a size-structured population model that simulated the change in the number of Atlantic sea scallops (per square meter) and size distribution within each 10-min square. Spatially explicit growth, and mortality rates, derived from the 2018 and 2020 stock assessments, were incorporated into the Atlantic sea scallop population model, enabling the emergence of observed gradients in size, growth rate, and abundance of Atlantic sea scallops in the simulations (NEFSC, 2018a; NMFS, 2022b). Atlantic sea scallop growth rates differ between the Mid-Atlantic and Georges Bank (NEFSC, 2018a), so region-specific growth parameters were applied in the model.

Region-specific estimates of specific growth rate (k, year^{-1}) reported in the stock assessment were used for the Mid-Atlantic and Georges Bank regions (NEFSC, 2018a). Asymptotic length (L_∞, mm) for the Mid-Atlantic and Georges Bank regions were obtained by fitting a von Bertalanffy length-growth rate relationship to length data obtained during the 2018 Atlantic sea scallop survey undertaken by the Virginia Institute of Marine Science Industry Cooperative Survey (Rudders et al., 2018) and the Northeast Fisheries Science Center (NEFSC) Integrated Sea Scallop and HabCam Research Survey (NEFSC, 2018b). The asymptotic length used in the von Bertalanffy curve fits for the Mid-Atlantic and Georges Bank regions was obtained from the observed maximum shell length from all dredge samples collected during the 2018 Atlantic sea scallop dredge surveys. Asymptotic lengths used in the population model corresponded to the 75th percentile of the largest observed size classes. The von Bertalanffy growth model implemented in SEFES constrains individuals from exceeding the specified L_∞. Therefore, to include the upper portion of the length frequency distribution, L_∞ was set to be larger than the observed values. The specific growth rate and asymptotic length estimated from the von Bertalanffy relationship for the Mid-Atlantic region were 0.564 year^{-1} and 140 mm and those for Georges Bank were 0.429 year^{-1} and 160 mm.

Natural mortality rates were specified separately for juveniles (defined as length less than 60 mm) and adults (lengths greater than 60 mm) in 10-min squares outside of the biological habitat. Juvenile specific mortality rate was specified to be 6.77 year^{-1} to remove recruits that settle in these regions within two years, thereby constraining fishable areas to those observed in the stock assessment. Juvenile mortality in the 10-min squares within the biological habitat was specified to give a distribution of individuals that was consistent with observed distributions from the stock assessment surveys. The specific mortality rate for these regions ranged from 1 year^{-1} to 0.23 year^{-1}.

A constant adult mortality rate of 0.23 year^{-1} was applied across all adult length classes. This mortality rate represents the average of estimates from the Mid-Atlantic (0.25 year^{-1}) and Georges Bank (0.20 year^{-1}) as reported in the stock assessment (NEFSC, 2018a). This mortality rate also provided the lower bound for the juvenile mortality. Adult mortality in this model was simplified to one rate, whereas the stock assessment includes size- and year-specific natural mortality rates that vary by region and area type (NEFSC, 2018a). SEFES fishing mortality rate, estimated from the relationship of biomass and associated landings in an area was 0.45 year^{-1}. The 2019 fully selected fishing mortality was estimated to be 0.34 year^{-1} (NEFSC, 2022b).

2.3. *Fishing Fleet*

2.3.1. *Atlantic sea scallop management and dynamics*

The formal adaptive rotational area management strategy implemented for the Atlantic sea scallop fishery uses spatial management to improve yield and minimize impacts on other fisheries and habitats (NEFSC, 2003). The spatial management areas are designated as open areas, access areas, and closed areas. Under this fishery rotational management program, access areas are opened to fishing or closed in response to observed stock biology conditions in those areas.

The catch of Atlantic sea scallops is allocated through days-at-sea and number of trips to access areas. When fishing in areas designated as open area, or in regions that are not closed to fishing or are part of a defined access area, fishing activity is measured in terms of days-at-sea. For grounds designated as access areas, fishing is permitted, but each fishing permit is allocated a possession limit (in pounds) for each designated area. These trip limits can be taken across as many trips as needed, as long as the possession limit is not exceeded. The access areas can be temporarily closed to protect small scallops, whereas closed areas are typically permanent closures established for reasons such as groundfish protection or habitat conservation. Management areas and allocation amounts can change annually based on the biology of the stock.

To implement the management area types within the SEFES model domain, Atlantic sea scallop vessels were permitted to target three distinct area types: the southern access area, the northern access area, and the open area (Fig. 1). Access area allocations in the simulations were informed by regulations outlined in the 2020 and 2021 fishing year allocations (Framework 33; NEFMC, 2021) (Table 1). In fishing years 2020 and 2021, 54,000 lbs. (24.5 metric tons) were allocated to rotational areas off New England, including Closed Area I, Closed Area II, and both Nantucket Lightship South Deep (Fig. 1). For the SEFES implementation, these areas were grouped into a single area type, the

Table 1
Atlantic sea scallop allocation by area type used in SEFES, relative to actual Rotational Access Areas, based on conditions from 2020 and 2021 fishing years. Rotational access area allocations are in days-at-sea and pounds (converted to metric tons, MT) for the open areas. Some 2020 open areas were closed in 2021, and therefore no allocations were assigned to those areas. Allocations reflect totals for a single full-time vessel.

Area Type	Rotational Access Area	Fishing Year 2020 Allocation	Fishing Year 2021 Allocation	SEFES Allocation
Open area	Days-at-sea	24 Days	24 Days	24 Days
Northern access area	Closed Area I	9000 lbs./4.1 MT	–	54,000 lbs./ 24.5 MT
	Closed Area II	18,000 lbs./ 8.2 MT	27,000 lbs./ 12.2 MT	
	Nantucket Lightship North	9000 lbs./4.1 MT	–	
	Nantucket Lightship South Deep	18,000 lbs./ 8.2 MT	27,000 lbs./ 12.2 MT	
Southern access area	Mid-Atlantic	36,000 lbs./ 16.3 MT	18,000 lbs./ 8.2 MT	36,000 lbs./ 16.3 MT
	Total	90,000 lbs./ 40.8 MT	72,000 lbs./ 32.7 MT	

northern access area, encompassing all access areas off New England, with an allocation of 54,000 lbs. (24.5 metric tons). The Mid-Atlantic rotational access area was allocated 36,000 lbs. (16.3 metric tons) in fishing year 2020 and 18,000 lbs. (8.2 metric tons) in 2021 (Framework 33; NEFMC, 2021). For the SEFES implementation, this area was designated as the southern access area, with an allocation of 36,000 lbs. (16.3 metric tons), consistent with the allocation in 2020, as the population dynamics model is based on survey data collected from 2018 to 2020. In the actual Atlantic sea scallop fishery, the open area allocation was 24 days-at-sea, which was used as the days-at-sea allocation for the simulated fishing vessels (NOAA, 2020, 2021) (Table 1). The remaining area within the biological habitat portions of the model domain was designated as open area. These allocations define the annual quota for a fishing boat independent of size, speed, or travel distance.

The commercial fishery lands Atlantic sea scallop adductor meats, which, similar to gonad weight, exhibit variation in yield both seasonally and regionally due to increases in food availability and decreases associated with spawning (Haynes, 1966; Serchuk and Smolowitz, 1989; Hennen and Hart, 2012). In discussions with Atlantic sea scallop industry, captains strategically target high yield areas in the fishery ahead of spawning. To reflect this behavior, the model incorporates seasonal variation by incentivizing vessels to fish in areas with higher yields throughout the season (Fig. 3). The proportion of total catch from each area was then used to define the monthly probability of a vessel fishing in a given area. In any given month, the combined probability of selecting a specific area also depends on how much of the annual quota has already been used. For each area, a residual quota was calculated based on the proportion of the current catch relative to the total allowable catch, as well as the remaining fishing days.

2.4. Fishing vessel behavior

Simulated fishing vessel activity is configured such that vessels are either at their home port, transiting to or from fishing locations, or actively fishing. Vessel activity is determined at the start of each hour and remains constant for that hour, with the total time spent on each activity accumulated. Vessels in port are given a wait time in numbers of hours, which limits the number of annual trips a vessel can take. Once the wait time reaches zero, a vessel attempts to depart port and transit to a fishing location. The ability to leave port depends on a 24-h weather forecast with safe operating conditions (described in Munroe et al., 2022). The simulated daily weather forecast, including wind forecasts, is

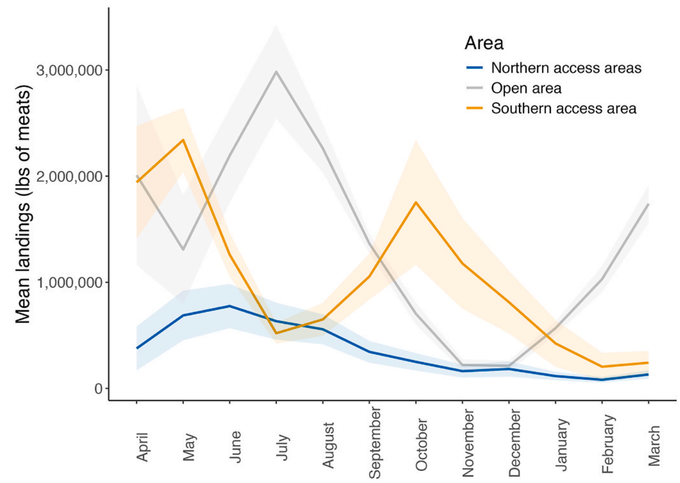

Fig. 3. Monthly-averaged scallop landings from 2018 to 2022 by area type: Northern access areas (includes Closed Area I, Closed Area II, and Nantucket Lightship areas), the southern access area (including the Mid-Atlantic Access Area), and the open area. The standard error for each area type is shown (shading). Data are from the NOAA Fisheries Quota Monitoring program for the Greater Atlantic Region data portal (NOAA, 2025b).

based on observations collected by seven meteorological buoys in the northern Mid-Atlantic (NOAA National Data Buoy Center) from 2015 to 2019. Observed wind speed and direction data were used to estimate the probability of winds exceeding 15 knots over a 24-h period, providing an assessment of weather conditions. If conditions are too windy, the vessel adds 24 h to the wait time and weather conditions are reassessed.

Once a vessel's wait time ends and weather conditions permit, the vessel will seek a fishing location based on the desirability factor for each area (for the given month) and the fraction of remaining quota for each area. If quota remains, a probability factor for each area is determined using the desirability factor, quota fraction, and the likelihood of choosing that area for the month. This simulated behavior mimics behavior in the Atlantic sea scallop fishery that results from higher yield in the southern grounds in the beginning of the fishing season, which slowly shifts northward as the fishing season progresses and as spawning of Atlantic sea scallops progresses from south the north (Fig. 3). Cumulative probabilities for the three areas are then calculated, and a random uniform draw assigns the fishing boat to an access area, or the open area based on these probabilities.

Once the fishing area is chosen, the 48-h wind forecast is evaluated to ensure favorable wind conditions for the fishing trip (Fig. 4). Unfavorable conditions reduce the trip duration by 24 h. If the adjusted trip duration remains positive, the best fishing location within the area based on the catch history for vessels from the same home port is determined. The fishing trip does not occur if the reduced trip duration is zero or negative (Fig. 4). Once the fishing area is identified, the vessel selects the 10-min square with the shortest fill time and highest desirability. The fill time for a fishing boat for each 10-min square in the selected area is determined by the average catch history for each square for the vessel's home port. The fill time can be shortened based on the desirability factor, which varies by latitude each 10-min square with the shortest fill time selected for the fishing trip (Fig. 4).

The duration of a fishing trip is estimated based on the selected fishing area, with the southern and northern access areas having a maximum trip duration of 8 days and the open area having a maximum of up to 12 days. Depending on forecast weather conditions, the fishing trip duration can be reduced by 24 h. Total annual catch is set for access areas (northern and southern) while total annual fishing days is set for the open area. For fishing locations in the open area, the fishing vessel remains inshore until it reaches the latitude of the fishing location, then turns east to the location. This simulated vessel behavior reflects

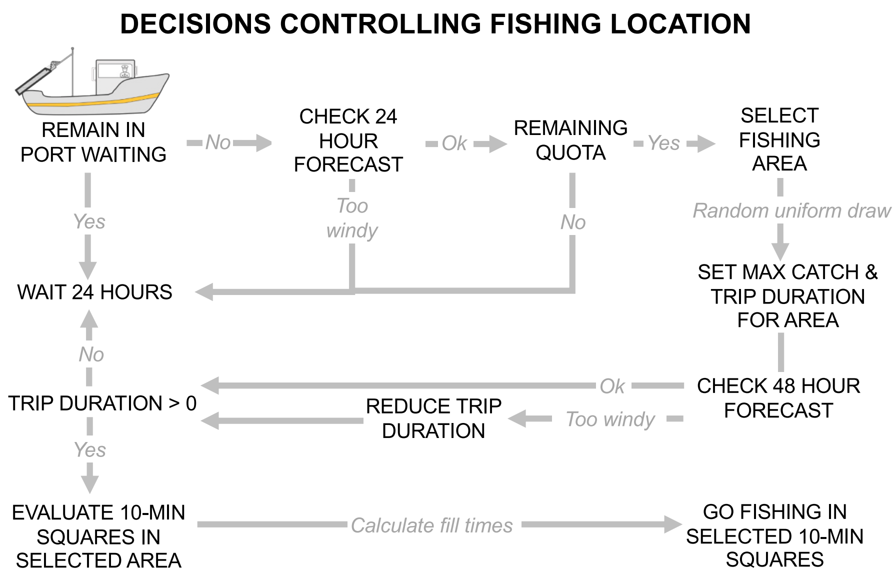

Fig. 4. Schematic of the decision tree used to determine fishing location for individual simulated Atlantic sea scallop fishing vessels that includes information from weather forecasts, fishing quota availability, and adjustments in trip duration due to weather.

feedback from Captains of Atlantic sea scallop fishing vessels, who reported staying inshore of the fishing area boundary, the demarcation between transit and active fishing, to avoid triggering regulations such as days-at-sea tracking, which would reduce their allocated fishing time when transiting to fishing grounds. The simulated vessel accumulates travel time to each 10-min square and determines fishing time by subtracting the transit time from the trip duration. Travel to the edge of the open area is not counted as fishing time but is included in the total days-at-sea. Travel time divided into time from the port to the western edge of the open area and from there to the fishing 10-min square, with only the latter counting against the time quota for the area. In contrast, direct travel time is applied to access areas, where trips are constrained not by days-at-sea but by the total catch weight for the trip.

Each of the simulated fishing vessels is assigned to a home port and vessels are combined to make a fishing fleet. Each fishing fleet departs from its home port allowing for spatial variability in the distribution of fishing effort and the acquisition of the allowed fishing quota. The memory of previous fishing trips resides with a vessel's home port and varies with the different home ports. The communication of fishing information and variability in searching skills among fishing vessels were specified using information gained through discussion with Atlantic sea scallop Captains from various ports to ensure the decisions implemented for the simulated vessels and fishing fleets reflected those made in the actual fishery.

Information provided by Captains of Atlantic sea scallop fishing vessels indicated that information about frequency of trips and specifics of fishing activity was typically exchanged among fishing vessels sharing the same port. The information among fishing vessels within the same home port typically included details on duration of trips, catch, and landings. Within the model, information sharing within the same home port was set at 100%, reflecting full communication among vessels from the same port. While information sharing between different home ports does occur, it was less common compared to exchanges within the same home port. The ability to share information among the ports was incorporated into the simulated fishing fleet behavior using a uniform probability distribution that allowed information to be shared at three levels (50%, 75% or 90%) for different simulations. The percent probability of sharing represents the percentage of trips for which the catch rate from a given fishing trip was shared with vessels based in other home ports.

Atlantic sea scallop fishing vessels operate under strict time constraints at sea, which limits opportunities for exploratory fishing and makes searching behavior relatively uncommon in the fishery. The random searching behavior allowed for the simulated fishing fleet vessels reflected this operational constraint. Eighty percent of the time, a Captain sampled a randomly selected 10-min square adjacent to the target 10-min square, conducted a 1-h tow, and recorded the resulting catch rate in the catch history for the home port. This approach assumes that the fishing vessels often move outside of the target fishing 10-min square.

Selection of a fishing location leverages port-level memories of past landings to minimize the time required to fill a fishing vessel based on expected catch rates. This memory history includes expected landings per unit effort (LPUE), specified in kilograms per hour for every fishable 10-min square. At the start of each simulation, each port has knowledge of the exploitable abundance for every 10-min square. Following each fishing trip originating from the port, the port's memory history is updated with the catch history for the 10-min squares that were fished. Information provided by Atlantic sea scallop Captains indicated that vessels keep extensive details of past fishing activities and use this information to make decisions about fishing locations. The relevance of this information can decrease over time as recruitment and mortality modify the distribution and abundance of Atlantic sea scallops. However, a simulated fishing vessel may still use outdated information to inform decision making, which was included in the simulations by assigning a memory weight factor that emphasized new or old information in the memory record. The memory factor specifies the weight to be placed on recent LPUE information. The updated memory of LPUE (M_{LPUE}) in a fished 10-min square is based on a memory factor (f), the previously remembered LPUE (Old_{LPUE}) and the new LPUE (New_{LPUE}) for that 10-min square as:

$$M_{LPUE} = fOld_{LPUE} + (1 - f)New_{LPUE} \tag{2}$$

Different simulations use one of four memory factors (0.2, 0.8, 0.98, 0.99) which controls the weight of new versus old catch rate in updating the memory. Memory weights of 0.2 and 0.8 place emphasis on using information from the previous 1–6 weeks, respectively, to make decisions about fishing. Memory weights of 0.98 or 0.99 base fishing decisions on performance over 7 months to over 1 year, respectively (Powell et al., 2015). The memory history for the simulations included an expected LPUE for every fishable 10-min square, which the fishing vessels use to select areas to fish on subsequent trips.

2.5. Fishing Fleet

The simulated fishing fleet was specified to represent the majority of vessels in the current Atlantic sea scallop fishery, based on information provided by management, industry representatives and fishing vessel captains. The model includes only vessels operating under a limited access permit, which accounts for 94.5% of the annual projected Atlantic sea scallop landings (NEFSC, 2018a). These vessels receive two types of allocations. The first is for fishing trips with a trip limit (typically 12,000–18,000 lbs. or 5,443–8,165 kg of meats) to designated rotational access areas (Table 1). The second allocation type consists of days at sea, which can be used in areas outside of closed or access areas. The remaining vessels operate under General Category permits, which are smaller day boats that are restricted to 600 lbs. (272 kg) per trip. This portion of the fleet accounts for approximately 5–6% of landings and was not included in the simulated fishing fleet.

The 2021 limited access permit data (GARFO, 2021) were used to identify the primary port for each limited access vessel, permit type (full time or part-time), and whether the vessel had a double or single dredge. Full-time permits provided vessels with the full annual allocation of trips and days-at-sea, while part-time permits have reduced allocation for vessels that have limited participation in the fishery. Double dredges are typically used by larger limited access vessels and have an increased efficiency because two dredges are towed simultaneously, while single dredges are more common on smaller vessels. In 2021 there were 351 limited access permits distributed across 31 ports in 7 states from Maine to North Carolina, indicating that many fishing ports along the eastern U.S. seaboard have vessels that target Atlantic sea scallops. However, for the purposes of the simulations, several primary ports were grouped based on geographic proximity. The ports of New Bedford (Massachusetts), Port Judith (Rhode Island), Cape May (New Jersey), and Hampton (Virginia) were selected because most of the Atlantic sea scallop fleet was assigned to a home port in New Bedford, Cape May, and Hampton, with the remaining vessels assigned to Port Judith (Fig. 1; Table 2). Fishing vessels were assigned to the nearest fishing port represented in the model. Vessels reporting principal ports such as Boston, Fairhaven, Hyannis, and others in Massachusetts were grouped under New Bedford (Massachusetts). Additionally, one vessel from Maine was grouped with New Bedford vessels. Similarly, those with principal ports in Barnegat Light, Atlantic City, and Point Pleasant, and others in New Jersey were grouped with those from Cape May (New Jersey). Stonington (Connecticut) vessels were combined with those from Point Judith (Rhode Island), and vessels from Virginia and North Carolina ports, including Seaford, Newport News, Wanchese, and others, were grouped under Hampton (VA).

The large Atlantic sea scallop fishing fleet consists of over 300 vessels. Each full-time vessel was counted as one full-time equivalent, while part-time vessels were considered 2/5 of a full-time vessel due to their smaller quota (receiving 2/5 of the days at sea compared to a full-time vessel). Each vessel (101 feet/30.8 m long) was assigned the same characteristics including dredge specifications (29.5 feet/9 m), catch capacity (3,000lb/day/1360.8 kg/day); steaming speed (10 knots) and fishing speed (4.5 knots). Vessels move around in the model domain and harvest Atlantic sea scallops and were allocated among home ports to reflect the distribution of observed vessels across the four key ports (Table 2).

The simulated catch of Atlantic sea scallops is based on a dredge that fishes at a rate measured in kilograms of meat per hour. Two commercial dredge configurations are commonly used in the Atlantic sea scallop fishery: the New Bedford Style dredge and the Coonamessett Farm Turtle Deflector Dredge, which was developed in 2013 (Smolowitz et al., 2012). The turtle deflector dredge, which is required seasonally (May 1-November 30) in the Mid-Atlantic and on Georges Bank to minimize sea turtle bycatch, was the dredge specified in the SEFES simulations. The simulated vessels were assigned the median reported efficiency from the turtle deflector dredge (46%; Gedamke et al., 2004; Gedamke et al., 2005; Walter et al., 2007; NEFSC, 2010), as it is seasonally required and there has been an increase in adoption of this dredge across the Atlantic sea scallop fleet. The selectivity of the turtle deflector dredge was parameterized (Roman and Rudders, 2019) to ensure that scallops under 80–90 mm have zero catchability, while those in the 80–90 mm size range can be caught but with very low selectivity, given the minimum landing size of 89 mm.

Table 2
Fishery permits by type (full-time or part-time), dredge (double or single) grouped by port location. Each full-time vessel was counted as one full-time equivalent, and part-time vessels were considered 2/5 of a full-time vessel due to their smaller quota (receiving 2/5 of the days at sea compared to a full-time vessel) to obtain the number of vessels in the simulated SEFES fishing fleet (full-time equivalents).

Port Location	Fishery permits			SEFES permits
	Full-time/ Double dredge	Full-time/ Single dredge	Part-time/ Single dredge	Full-time equivalents
New Bedford, MA	129	16	10	149
Point Judith, RI	3	2	1	5
Cape May, NJ	68	25	12	98
Hampton, VA	64	11	10	79
Total	264	54	33	331

2.6. Simulation design and validation

The potential impacts of offshore wind energy development on the Atlantic sea scallop fishing industry are likely to be realized through effects on fishing locations and transit routes for fishing vessels. Five simulation scenarios (Table 3) were designed to evaluate restrictions on fishing location and vessel transit within current wind lease areas and anticipated future development areas (Fig. 1). The first scenario (‘no restrictions’) assumes no offshore wind energy development and no restrictions on fishing or transit, which provides a baseline for evaluating the effects of restrictions imposed on fishing and transit within existing leases (‘restricted fishing’ and ‘restricted fishing and transit’ scenarios) and existing and anticipated future lease areas (‘future restricted fishing’ and ‘future restricted fishing and transit’ scenarios) (Table 3). For simulations with imposed operational restrictions related to wind development, a model grid cell was considered within a wind energy lease area if the lease area or potential future development area polygon, including a 2NM (~3.6 km) buffer, overlapped with 50% or more of the grid cell (Fig. 1).

Each scenario was assessed with an ensemble of 200 simulations.

Table 3
Scenarios implemented with SEFES to assess the impacts of fishing and transiting restrictions imposed by offshore wind energy development lease areas on the Atlantic sea scallop fishery.

Scenario	Offshore wind energy lease area configuration	Restriction
No restrictions	None/status quo	None
Restricted fishing	Existing lease areas	No fishing, transit allowed
Restricted fishing and transit	Existing lease areas	No fishing nor transit
Future restricted fishing	Existing lease areas + future development	No fishing, transit allowed
Future restricted fishing and transit	Existing lease areas + future development	No fishing nor transit

Variability in the 200 simulations was introduced via communication among fishing ports and the Captain's memory as follows. The catch history resides with a port and all fishing boats associated with a port use this information as well as information from the annual survey. Communication was varied by 0.5, 0.75 and 0.9, which sets the percent catch history information that is exchanged among fishing ports. The ability of a Captain to apply previous fishing information, the memory, was varied by 0.2, 0.8, 0.98 and 0.99, with the values indicating the percent of previous information that Captain uses with the remaining percent provided by new fishing information. The twelve combinations of the communication and memory values were randomly applied to produce the 200 simulations used for the ensemble.

Each of the 200 simulations was implemented for 300 years. No fishing was imposed during the first 100 years to allow the Atlantic sea scallop population dynamics to stabilize. Atlantic sea scallops live for approximately 20 years (NEFSC, 2018a; NMFS, 2022b) and the 100-year simulation allows 4 to 5 population cycles for recruitment, growth, and mortality to come into equilibrium. The second 100 years allowed fishing, but with no restrictions imposed by offshore wind energy development. This 100-year simulation started with the equilibrium Atlantic sea scallop population from the first 100 years and again 4 to 5 population cycles are sufficient to establish an equilibrium between the Atlantic sea scallop biomass and fishing mortality. Restrictions related to offshore wind energy lease regions were imposed on fishing and vessel operations in the final 100 years of the simulation that was initialized with the equilibrium values from the second 100-year simulation. Simulations without restrictions imposed by wind energy lease regions also continued during the last 100 years. The final 50 years of the 300-year simulation were used for analysis. The metrics obtained from the simulations used to assess the effect of offshore wind energy lease areas on the Atlantic sea scallop fishery were the number of fishing trips, total hours spent steaming and fishing, catch, and LPUE (kilogram per hour).

The population dynamics model was initialized with the Atlantic sea scallop biomass distribution and run for 100 years without fishing to allow the population to come into equilibrium with specified growth, mortality and recruitment. The total and exploitable (>90 mm) observed biomass from 2017 to 2019, reported in the 2020 Atlantic sea scallop management track assessment (NMFS, 2022b), was used to compare against the simulated Atlantic sea scallop equilibrium biomass. This equilibrium simulation served as a reference scenario, capturing the broad spatial patterns of Atlantic sea scallop distribution. Validation of the set of reference simulations was done using input from the Atlantic sea scallop management representatives to ensure that simulations represented the current state of the fishery as reflected by current knowledge. Data on fishing trips from 2018 to 2022 for the limited access sea scallop fishery were obtained from the Greater Atlantic Regional Fisheries Office (B. Galuardi, personal communication, 2023). These data allow calculation of time at sea, catch, LPUE (kilogram per hour) for trips over the identified time period. Equivalent metrics (time at sea, catch, LPUE) were calculated for the simulations during the last 50 years of the 200 model runs for the reference scenario (no restrictions). The last 50 years of the simulation used for analysis do not represent projections extending 50 years into the future after offshore wind construction but rather, each year is treated as a steady-state replicate to capture short-to medium-term effects.

3. Results

3.1. Model validation

The Atlantic sea scallop stock assessment update was completed in 2020, and provided biomass values (total and exploitable) for 2017 to 2019 (NEFSC, 2022b). Total biomass estimates ranged from about 147, 000 metric tons to about 193,000 metric tons (Fig. 5A). The simulated Atlantic sea scallop biomass of 195,000 metric tons obtained from the scenario with no restrictions imposed on fishing was comparable, ~1% above the 2017 estimate and ~33% over the 2019 biomass estimate (Fig. 5A). Exploitable biomass (>90 mm) ranged from about 90,000 metric tons to 126,000 metric tons (Fig. 5B). The simulated exploitable biomass of 169,000 metric tons obtained from the scenario with no restrictions imposed on fishing was larger than observed biomass estimates (between 34 and 88% larger) (Fig. 5B).

Simulated annual catch of Atlantic sea scallops was within the range of annual catches reported from 2018 to 2022, suggesting the simulations captured a realistic range of landings (Fig. 5C). Simulated days-at-sea was about 42% lower than the reported values from 2018 to 2021, but similar to the values reported for 2022 (Fig. 5D). The LPUE was similar to values reported for 2018 and 2019, differing by less than 4%, and was approximately 27% higher than values reported for 2020–2022 (Fig. 5E). These comparisons indicate that, on average, the simulations realistically capture the dynamics of the Atlantic sea scallop population and the fishing fleet.

3.2. Effect of fishing and transiting restrictions

The percent change in simulated catch, LPUE, time at sea and fishing time, and biomass obtained from the simulations show that fishing and/

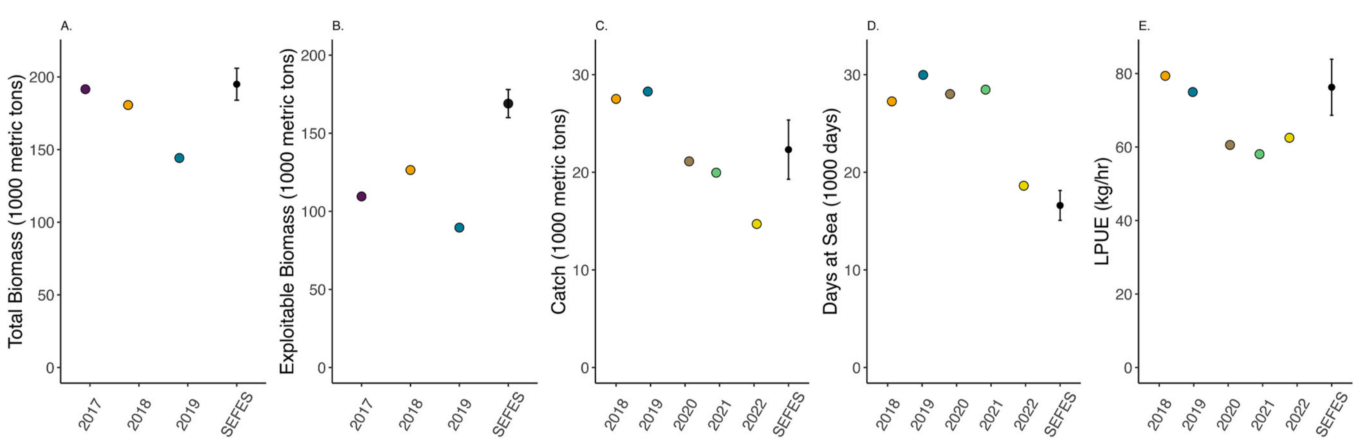

Fig. 5. Comparison of observed (colored circles) and simulated (black circle) A) total biomass B) exploitable biomass (>90 mm); Observed biomass estimates (total and exploitable) are from the 2020 management track assessment update (NEFSC, 2022b). The simulated biomass value is the average and standard deviation calculated from the final 50 years of the no restrictions simulation. C) catch D) total days at sea (open and access areas), and E) landings per unit effort (LPUE). Observed fisheries data obtained upon request from the Greater Atlantic Regional Fisheries Office (B. Galuardi, personal communication, 2023). The simulated value is the average and standard deviation calculated from the final 50 years of the no restrictions simulation.

or transit restrictions imposed by offshore wind energy lease areas have minor impact on the Atlantic sea scallop fishery (Table 4; see Supplementary Table S1 for mean and standard deviation values). Catch showed a slight positive change for simulations with the smaller wind footprint; the larger wind footprint resulted in a negative decrease in catch (Table 4). Overall there were small increases in LPUE for all scenarios, however, area-specific changes in LPUE showed increases in northern areas, but steady decline in southern areas, with reductions reaching nearly 4% under increasing wind and transit restrictions. Total time at sea (port to port) and total fishing time both declined as restrictions increased. Small increases in total stock biomass were observed with increasing restrictions. The largest negative effect of the wind energy lease area restrictions was on Atlantic sea scallop biomass outside the wind energy lease areas. Although total biomass slightly increased, effort displacement resulted in a reduction in biomass outside the wind farm area. Simulations that used the larger footprint of the current and planned wind energy lease area configuration (future scenarios) showed the largest negative change in total stock biomass outside the lease area (Table 4).

Imposed restrictions on areas accessible to fishing and transit produced spatial shifts in simulated fishing trips, measured as changes in the total number of trips per model grid cell (Fig. 6). The future wind lease area, which encompasses existing leases and anticipated future lease areas, resulted in more variability in trip numbers relative to the existing lease areas (Fig. 6a, b vs Fig. 6c, d). Transit scenarios (restricted fishing and future restricted fishing) resulted in less disruption to fishing activity, with smaller changes in trip numbers. The simulations without transit (restricted fishing and transit and future restricted fishing and transit) through the lease areas showed concentrated decreases in fishing effort and fewer increases in fishing trips, suggesting that transit restrictions amplify localized impacts on fishing. Allowing transit through the lease areas appeared to mitigate some of the negative impacts on fishing activity. Changes in fishing trips were more pronounced around the southern lease areas, where decreases in fishing trips overlapped with lease areas and increases in fishing trips were concentrated offshore, particularly in the future wind lease area scenarios (Fig. 6c, d). In the northern regions, less variability in fishing trips occurred with smaller, more localized pockets of increases or decreases near the boundaries of the wind lease areas (Fig. 6c, d).

Table 4
Percent change (%) in annual catch, average landings per unit effort (LPUE) across all, northern and southern access areas, days at sea, time fishing, total stock biomass, and total stock biomass outside the wind energy lease areas from the simulations that restricted fishing in the wind energy lease areas (restricted fishing, restricted fishing and transit) and simulations that restricted fishing and transiting in the wind energy lease areas (future restricted fishing, future restricted fishing and transit). The percent change was calculated relative to the simulation with no imposed restrictions on fishing or transiting in the wind energy lease areas (no restrictions). Negative changes are indicated by bold type.

Metric	Restricted fishing	Restricted fishing & transit	Future restricted fishing	Future restricted fishing & transit
Catch	0.14%	0.33%	**−1.11%**	**−1.32%**
LPUE (all)	0.27%	0.78%	0.69%	0.23%
LPUE (Northern Areas)	1.05%	1.48%	2.57%	2.82%
LPUE (Southern Areas)	**−0.70%**	**−0.33%**	**−2.96%**	**−3.77%**
Sea Time	**−0.14%**	**−0.45%**	**−1.64%**	**−1.64%**
Fish Time	**−0.18%**	**−0.44%**	**−1.69%**	**−1.52%**
Total Stock Biomass	0.00%	0.51%	1.54%	1.03%
Total Stock Biomass (outside lease area)	**−4.10%**	**−3.59%**	**−8.72%**	**−9.23%**

The restrictions on transiting and fishing imposed by wind energy lease areas resulted in negative values for nearly all metrics used to evaluate the effects for each fishing home port (Fig. 7; see Supplementary Table S2 for mean and standard deviation values). The number of annual fishing trips decreased for all ports, with larger reductions under future scenarios. Similarly, changes in time fishing per port also declined across all ports reflecting reductions in fishing activity, with larger declines observed for future scenarios. Vessel travel time decreased for all ports (up to 4%), suggesting that vessels may adjust their routes to closer fishing grounds or reduce overall activity rather than spend additional time transiting around lease areas. Larger decreases in vessel travel time were observed for northern ports (Massachusetts and Rhode Island; Fig. 7A and B), which are closer to Atlantic sea scallop resources off New England, allowing the vessel quota to be acquired by fishing at nearby locations and use of days-at-sea. As a result, these vessels make fewer trips to the southern portion of the Atlantic sea scallop resource, reducing their travel time. Southern ports (Cape May and Virginia; Fig. 7C and D) had minor declines in travel time but larger declines in fishing activity. LPUE remains stable with minor increases observed in northern ports. The future scenario, which included a larger wind lease footprint, generally resulted in larger declines across metrics as compared to the smaller, current lease footprint. This suggests that the expansion of the wind lease areas can amplify reductions to fishing activity.

4. Discussion

Evaluation of Risks. Previous estimates of the risks to the Atlantic sea scallop fishery on the Northeast U.S. continental shelf from offshore wind energy development are based on prior fishing behavior and do not include fishing route changes or shifts in fishing locations due to the placement of wind farm leases areas (RI DEM, 2017). As such, these estimates may not accurately reflect consequences and impacts to the Atlantic sea scallop fishery. The simulation-based analysis used in this study allows evaluation of limitations imposed on fishing and vessel transiting by current and future configurations of offshore wind energy lease areas on the Atlantic sea scallop fishery. The simulations showed that the wind energy lease areas resulted in proportionally small impacts (all under 4%) on time at sea, time spent fishing and catch. The percentage of total catch in the no restriction simulation being caught within the lease areas was low, 0.55% and 3.13% for the smaller and larger windfarm footprints, respectively. Given the limited overlap between fishing activities and the lease areas, these negligible impacts observed for time at sea, time spent fishing, and catch are expected. However, the high value of the Atlantic sea scallop fishery means that even small shifts in the fishery could translate into substantial changes in revenue. For example, with the fishery grossing approximately $500 million annually, changes to catch of 0.55% and 3.13% could result in losses of USD 2.8 million and 15.7 million, respectively.

Total stock biomass was essentially unaffected by the restrictions imposed on fishing and the fishing fleet by the wind energy lease area configurations. The largest negative effect of the wind energy lease area restrictions was on Atlantic sea scallop biomass outside the wind energy lease areas. Although total biomass remains unchanged, effort displacement leads to a reduction in biomass outside wind farm areas by approximately 10%. Therefore, the remaining portion of the stock experiences increased fishing pressure as displaced effort is concentrated outside of wind lease area. Simulated biomass does not account for additional factors which could change due to offshore wind development that could impact Atlantic sea scallop population dynamics such as impacts to habitat from cabling, shifts in community composition, changes to oceanographic dynamics, and other unmodelled environmental effects, as these factors were not included in the simulations.

Restrictions imposed on fishing location and vessel transiting resulted in spatial redistribution of simulated fishing trips, with larger changes associated with the larger proposed future wind energy lease

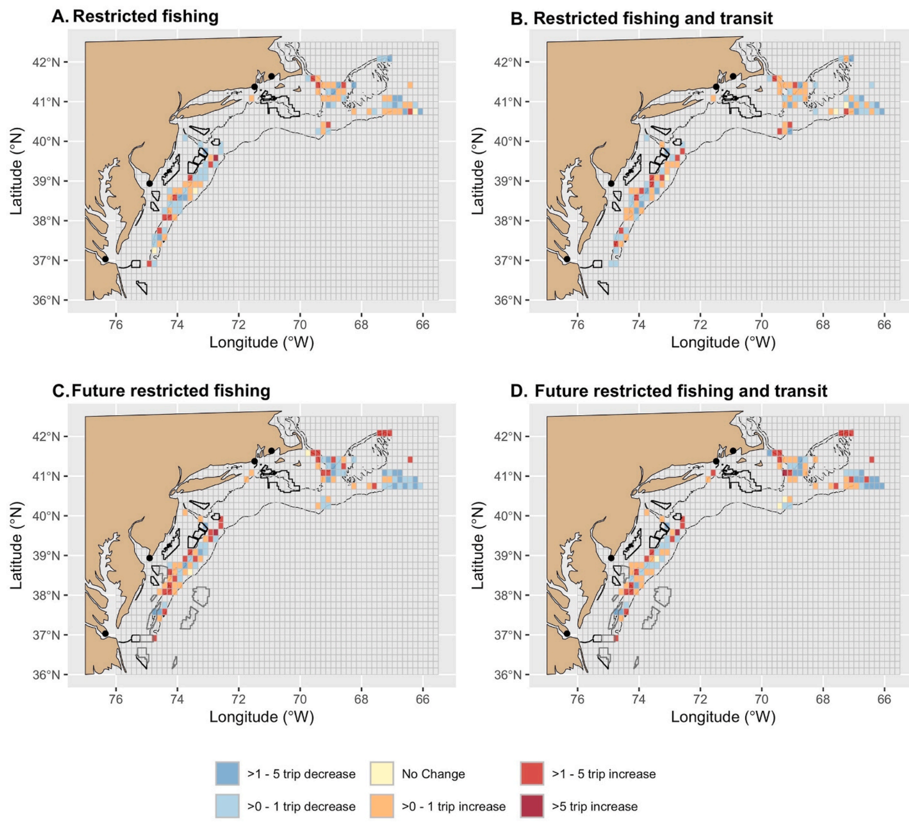

Fig. 6. Simulated Atlantic sea scallop fishing effort displacement, indicated by the change in the average number of trips per model grid cell per year under four scenarios (A) transit allowed but no fishing in existing lease areas (restricted fishing); (B) neither transit nor fishing in existing lease areas (restricted fishing and transit); (C) transit allowed but no fishing in existing and proposed areas (future restricted fishing); and (D) neither transit nor fishing in existing and proposed lease areas (future restricted fishing and transit). Displacement in each model grid was calculated for each simulation scenario relative to the average annual days fishing in that grid cell with no transit or fishing restriction (no restrictions). A decrease in average effort for a model grid cell under a particular scenario indicates operational restrictions led to less (more) time fishing in that area. Offshore wind leases are shown as black (existing lease areas) and grey (proposed lease areas) polygons and port landing locations for the modeled fleet are marked with black circles and include from north to south: New Bedford, MA; Port Judith, RI; Cape May, NJ; and Hampton, VA.

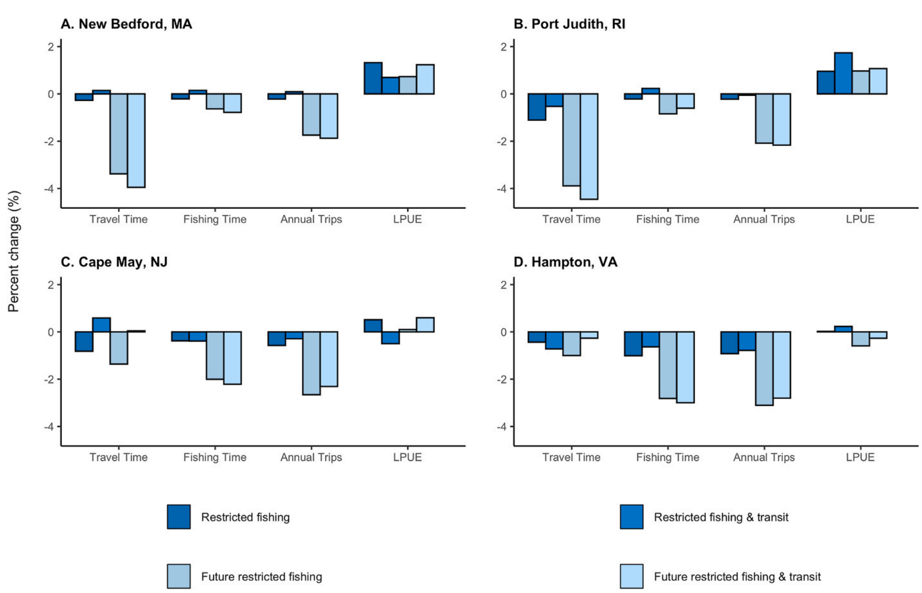

Fig. 7. Simulated percent change (%) in travel time, fishing time, annual trips and landings per unit effort (LPUE) for Atlantic sea scallop fishing fleets with home ports of A) New Bedford, MA, B) Port Judith, RI, C) Cape May, NJ and D) Hampton, VA obtained for scenarios that restricted fishing (restricted fishing and future restricted fishing) and scenarios that restricted fishing and transiting (restricted fishing and transit and future restricted fishing and transit) in the wind energy lease areas (colors). Each metric was calculated relative to the reference simulation (no restrictions) with no imposed restrictions on fishing or transit in the wind energy lease areas.

area footprint, particularly in the southern part of the Atlantic sea scallop fishery region. While fishing is not explicitly prohibited within wind energy lease areas, uncertainty remains about the extent of fishing that will occur once these areas are developed. Concerns include anticipated increases in navigational challenges (Copping et al., 2016), disruptions to fishing operations (ten Brink and Dalton, 2018), increased likelihood of gear entanglement, damage or loss (Hogan et al., 2023), and validity of insurance and liability (Hooper et al., 2015). As a result, vessel operators may increasingly shift effort to less profitable areas, as there is growing hesitation to fish within offshore wind energy development areas. The simulations that allowed vessels to transit through the wind energy lease areas showed smaller impacts to fishing, indicating that transiting these areas can mitigate some of the negative impacts on the fishing industry. In contrast, scenarios without vessel transiting wind energy lease areas led to decreases in fishing trips, as vessels were unable to pass through the lease areas, highlighting that transit restrictions amplified localized disruptions especially in the southern part of the Atlantic sea scallop range. Chaji et al. (2024) suggest that Atlantic sea scallop vessels may avoid transiting through wind energy areas, which can increase transit times, raise operating costs, and reduce fishing time, ultimately lowering trip revenue. These impacts are likely to disproportionately affect the limited access fleet, which already undertakes longer trips farther offshore, particularly during days-at-sea trips in open areas where fishing time is constrained.

Evaluation of Restrictions to Fishery. The impacts of restrictions on simulated fishing location and vessel transiting had minor impacts (all under 5%) at the level of the fishing fleet home ports, with only small variations in fishing effort and fishing trip numbers observed for the different offshore wind energy lease area scenarios. Approximately 50% of Atlantic sea scallop fishing vessels are based in New Bedford, Massachusetts. In recent years, vessels from southern ports have been relocating to New Bedford for the fishing season, taking an increasing percentage of their trips from there. This shift is driven by the changing distribution of Atlantic sea scallop resources and better market access. While the port-specific impacts may seem small, they could exacerbate the challenges faced by southern ports, making them even less appealing, and potentially lead to a continued or increased shift of vessels toward northern ports. Similarly, the SEFES surfclam model found that southern ports were disproportionally impacted, with simulated fishery revenues in Atlantic City, New Jersey declining by approximately 5–25% depending on the simulation scenario (Scheld et al., 2022).

While the Atlantic sea scallop resource is considered healthy, with the stock not overfished and overfishing not occurring, recent biomass surveys have shown a decline, with 2023 levels remaining low compared to the 2014–2019 peak years (NOAA, 2025c). Biomass declines have been observed throughout much of Georges Bank and the Mid-Atlantic Bight, with below-average recruitment in the Mid-Atlantic since 2013. The harvestable-size Atlantic sea scallop population projected for the 2025 fishing year is also low, resulting in reduced allocations for the fishery (NOAA, 2025a). Environmental changes, particularly rapid warming, are likely increasing Atlantic sea scallop mortality, especially at the southern end of their range, where habitats have experienced significant warming over the past several decades (Saba et al., 2016; Zang et al., 2023). The limited thermal tolerance of scallops makes them particularly vulnerable to warming bottom temperatures (Hare et al., 2016). The declining biomass in the southern part of the Atlantic sea scallop range supports a northward and offshore shift in the resource that requires fishing vessels in the southern fleet to travel farther to fish to sustain their catches. The Atlantic sea scallop fishery faces increasing risks from short term offshore development and long-term climate change, underscoring the need for adaptive management strategies to mitigate the combined and potentially significant impacts on this economically vital resource. Offshore wind development provides renewable energy to combat climate change but also interacts with other ocean users and resources, clean energy expansion should be balanced with appropriately sited development to minimize conflict.

Evaluation Approach. The agent-based model framework used in this study allows investigation of the effects of environmental changes, such as temperature-induced range shifts, on fish stock distribution, fishery performance, and management policies (see applications for Atlantic surfclams, Powell et al., 2015, 2016; Kuykendall et al., 2017, 2019; Borsetti et al., 2023; Spencer et al., 2024a, b). The DISPLACE model, an agent-based model applied to fishery stocks in the North Sea and Baltic Sea, uses a similar approach to evaluate the ecological and economic consequences of fisheries management strategies (Bastardie et al., 2014). The activities of individual fishing vessels and their decision-making processes in response to changes in fishery management, economic incentives, and stock conditions are simulated by DISPLACE. Like SEFES, DISPLACE offers valuable insights into spatial management challenges and conflicts, highlighting the effectiveness of agent-based modeling in understanding and resolving complex, spatially distributed resource issues. Both SEFES and DISPLACE highlight the utility of agent-based models in understanding and resolving complex spatial conflicts, offering robust tools for more effective and adaptive management of natural resources. Both models demonstrate the usefulness of simulations to analyze and resolve spatial conflicts by including the behaviors of individual agents and their impact on larger systems, offering valuable tools for adaptive and sustainable management.

The Atlantic sea scallop fishery is more complex than the Atlantic surfclam fishery that was the initial application of SEFES. Unique features of the Atlantic sea scallop fishery, such as adaptive rotational area management strategy and unique vessel dynamics, were parameterized and incorporated into SEFES. Key differences in the Atlantic sea scallop fishery and Atlantic surfclam fisheries in how the fisheries responded to similar offshore wind restrictions emerged from the simulations. For the Atlantic surfclam fishery, which is more spatially constrained, offshore wind energy development led to notable reductions in catch and economic consequences for affected ports (Scheld et al., 2022). In contrast, the Atlantic sea scallop fishery showed minimal effects, as its primary fishing areas had much lower overlap with offshore wind energy lease areas. These contrasting outcomes underscore that the impacts of offshore wind energy development are driven by the specific characteristics and spatial dynamics of each fishery. The degree of spatial overlap between fishing activities and wind energy lease areas has a crucial role in determining the scale of disruption. The differences in the impacts on these two fisheries demonstrates the need for fishery-specific modeling approaches that account for unique dynamics and spatial constraints to accurately assess the potential consequences of offshore wind energy development. Within the same region, fisheries that use similar gears can experience vastly different impacts from offshore wind energy development. The unique characteristics of each fishery such as spatial overlap with wind lease areas, management practices, and fleet dynamics play a critical role in determining the scale and nature of the impact, underscoring the need for tailored approaches when assessing the potential effects of offshore wind energy development on regional fisheries.

The Atlantic sea scallop fishery is a complex system. The SEFES framework incorporates much of this complexity, especially that related to adaptive rotational area management and fishing vessel characteristics. While the simulated metrics may not precisely match observed fishery values, they fall within the approximate magnitude and are similar in scale, reflecting the general trends in the fishery. Inclusion of fine-scale variations in fishing behavior or localized economic impacts would refine the results from this study but are unlikely to change the overall outcomes. The simulation results from this study are consistent with those reported in Chaji et al. (2024) which used a different approach, highlighting the robustness of the conclusions. The spatially explicit agent-based model presented here offers a powerful tool to anticipate how the Atlantic sea scallop fishery may change in light of offshore wind development, while also enhancing our understanding of the factors that will shape its future viability.

CRediT authorship contribution statement

Sarah Borsetti: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Daphne M. Munroe:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **John M. Klinck:** Writing – original draft, Visualization, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrew M. Scheld:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Eileen E. Hofmann:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Conceptualization. **Eric N. Powell:** Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **David B. Rudders:** Writing – original draft, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table S1
Fishing activity and biomass metrics across simulation scenarios (Table 4). Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Average catch is in 1000 metric tons, average LPUE is shown as kilograms per hour fished, average sea and fishing time are shown as hour per trip and biomass are shown in 1000 metric tons. Standard deviations are presented beneath means in italics.

Metric	No restriction	Restricted fishing	Restricted fishing & transit	Future restricted fishing	Future restricted fishing & transit
Average Catch	22.321 *3.036*	22.353 *3.069*	22.395 *3.056*	22.073 *2.901*	22.026 *2.983*
Average LPUE (all)	76.266 *7.627*	76.473 *7.481*	76.864 *7.622*	76.791 *7.126*	76.442 *7.05*
Average LPUE (Northern Areas)	81.332 *10.934*	82.185 *11.337*	82.536 *11.583*	83.423 *10.837*	83.626 *11.141*
Average LPUE (Southern Areas)	72.651 11.893	72.146 10.792	72.409 10.729	70.499 9.894	69.911 9.797
Average Sea Time	398.522 *36.681*	397.973 *36.033*	396.709 *37.752*	391.995 *39.581*	391.981 *39.431*
Average Fishing Time	292.604 *27.071*	292.074 *26.598*	291.325 *27.923*	287.655 *29.249*	288.143 *28.767*
Average Total Stock Biomass	195 *12*	195 *12*	196 *12*	198 *11*	197 *11*
Average Total Stock Biomass (outside lease area)	195 *12*	187 *12*	188 *12*	178 *11*	177 *11*

Table S2
Fishing activity metrics across simulation scenarios for different fishing ports (Fig. 7). Each value displayed is the mean across 10,000 observations representing 50 years from each of 200 model simulations. Average travel time and average time fishing are shown as hours per trip. Average LPUE is shown as kilograms per hour fished. Standard deviations are presented beneath means in italics.

Port	Metric	No restriction	Restricted fishing	Restricted fishing & transit	Future restricted fishing	Future restricted fishing & transit
New Bedford, MA	Average Travel Time	36.601 *4.257*	36.502 *4.665*	36.654 *4.466*	35.364 *4.786*	35.155 *4.812*
	Average Fishing Time	136.944 *11.751*	136.654 *12.131*	137.147 *11.553*	136.076 *12.181*	135.874 *12.417*
	Annual Trips	944.156 *80.004*	942.069 *86.720*	945.017 *82.706*	927.681 *95.272*	926.458 *95.662*
	Average LPUE	74.699	75.685	75.218	75.244	75.618

(continued on next page)

Table S2 (*continued*)

Port	Metric	No restriction	Restricted fishing	Restricted fishing & transit	Future restricted fishing	Future restricted fishing & transit
		8.078	*8.833*	*8.267*	*8.077*	*8.124*
Port Judith, RI	Average Travel Time	1.149 *0.164*	1.137 *0.173*	1.143 *0.169*	1.105 *0.174*	1.098 *0.178*
	Average Fishing Time	4.442 *0.523*	4.432 *0.516*	4.452 *0.495*	4.405 *0.505*	4.415 *0.499*
	Annual Trips	30.370 *3.478*	30.302 *3.602*	30.352 *3.498*	29.737 *3.749*	29.712 *3.817*
	Average LPUE	81.250 *18.059*	82.027 *16.888*	82.660 *16.615*	82.037 *16.209*	82.118 *15.151*
Cape May, NJ	Average Travel Time	32.535 *4.424*	32.269 *4.349*	32.726 *4.268*	32.093 *4.594*	32.550 *4.455*
	Average Fishing Time	86.792 *8.701*	86.462 *9.042*	86.456 *8.639*	85.051 *9.477*	84.870 *9.706*
	Annual Trips	633.322 *69.271*	629.685 *70.707*	631.492 *67.723*	616.493 *73.277*	618.696 *74.691*
	Average LPUE	76.411 *9.471*	76.803 *9.706*	76.031 *8.710*	76.486 *8.754*	76.866 *9.045*
Hampton, VA	Average Travel Time	35.632 *4.893*	35.477 *4.755*	35.375 *4.819*	35.276 *4.900*	35.537 *4.708*
	Average Fishing Time	64.427 *6.758*	63.777 *7.171*	64.018 *6.790*	62.612 *7.752*	62.496 *7.734*
	Annual Trips	521.758 *61.812*	516.954 *62.350*	517.675 *61.239*	505.566 *65.295*	507.139 *64.413*
	Average LPUE	79.146 *10.652*	79.163 *10.163*	79.330 *10.162*	78.678 *9.922*	78.934 *10.277*

Data availability

Data will be made available on request.

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