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Sarah Borsetti

Daphne M. Munroe

Andrew M. Scheld

Eric N. Powell

John M. Klinck
Old Dominion University, jklinck@odu.edu

See next page for additional authors

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Authors

Sarah Borsetti, Daphne M. Munroe, Andrew M. Scheld, Eric N. Powell, John M. Klinck, and Eileen E. Hofmann

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Potential Repercussions of Offshore Wind Energy Development in the Northeast United States for the Atlantic Surfclam Survey and Population Assessment

Sarah Borsetti*
Virginia Institute of Marine Science, William & Mary, 1370 Greate Road, Gloucester Point, Virginia 23062, USA

Daphne M. Munroe
Haskin Shellfish Research Laboratory, Rutgers the State University of New Jersey, 6959 Miller Avenue, Port Norris, New Jersey 08349, USA

Andrew M. Scheld
Virginia Institute of Marine Science, William & Mary, 1370 Greate Road, Gloucester Point, Virginia 23062, USA

Eric N. Powell
Gulf Coast Research Laboratory, University of Southern Mississippi, 703 East Beach Drive, Ocean Springs, Mississippi 39564, USA

John M. Klinck and Eileen E. Hofmann
Center for Coastal Physical Oceanography, Old Dominion University, 4111 Monarch Way, Norfolk, Virginia 23508, USA

Abstract
The Atlantic surfclam *Spisula solidissima* fishery, which spans the U.S. Northeast continental shelf, is among the most exposed to offshore wind energy development impacts because of the overlap of fishing grounds with wind energy lease areas, the hydraulic dredges used by the fishing vessels, and the location of vessel home ports relative to the fishing grounds. The Atlantic surfclam federal assessment survey is conducted using a commercial fishing vessel in locations that overlap with the offshore wind energy development. Once wind energy turbines, cables, and scour protection are installed, survey operations within wind energy lease areas may be curtailed or eliminated due to limits on vessel access, safety requirements, and assessment survey protocols. The impact of excluding the federal assessment survey from wind energy lease areas was investigated using a spatially explicit, agent-based modeling framework that integrates Atlantic surfclam stock biology, fishery captain and fleet behavior, and federal assessment survey and management decisions. Simulations were designed to compare assessment estimates of spawning stock biomass (SSB) and fishing mortality (*F*) for scenarios that excluded the survey from (1) wind energy lease areas or (2) wind energy lease areas and potential wind energy lease areas ("call areas"). For the most restricted scenario, the simulated stock assessment estimated 17% lower SSB relative to an unrestricted survey, placing it below the SSB target. The simulated *F* increased by 7% but was still less than the accepted *F* threshold. Changes in biological reference points were driven by the inability to access the Atlantic surfclam biomass within the wind energy lease areas. Deviations in

*Corresponding author: seborsetti@vims.edu
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reference points reflected the proportion of the population excluded from the survey. Excluding the Atlantic surfclam assessment surveys from the regions designated for offshore wind development can alter long-term stock assessments by increasing uncertainty in metrics that are used to set fishing quotas.

The demand for large-scale renewable energy in the United States has stimulated significant investment of resources in the development of offshore wind energy infrastructure (BOEM 2020b). Existing and potential offshore wind energy lease areas for the U.S. East Coast are intended to meet the national target of generating 30 GW of offshore wind capacity by 2030 and to meet the goal of net zero emissions by 2050 (BOEM 2020b). As of 2021, over 687,965 ha (1.7 million acres) were leased for offshore wind energy projects with a total technical capacity of 25 GW on the U.S. Northeast continental shelf (BOEM 2020a, 2021). An additional 706,996 ha (1.75 million acres) are under consideration for potential wind energy leasing (A. L. Randall and colleagues, draft report, https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/BOEM_NCCOS_JointReport_DraftWEAs_FINAL.pdf). This expansion of the offshore wind industry overlaps spatially with longstanding user groups of the U.S. Northeast continental shelf, thereby setting up the potential for use conflicts (Methratta et al. 2020). Indeed, the overlapping use of commercial fishing industries and the emerging offshore wind energy industry has already generated concerns about impacts on fished stocks, commercial fishing activity, and fisheries science and management (BOEM 2020b).

The National Marine Fisheries Service (NMFS) conducts ship-based trawl and dredge surveys to provide stock biomass assessments for federally managed fish and shellfish resources on the U.S. Northeast continental shelf (Hare et al. 2022). The fisheries resource surveys use a stratified design with randomly selected sampling locations within geographic strata (Hare et al. 2022); the results of these surveys provide inputs for regional fisheries management councils to develop regulations for a fishery, assess stock status relative to established reference points, and set catch quotas for federally managed species (Lynch et al. 2018). Decades of stock biomass estimates from federal assessment surveys have provided estimates of fishing mortality (F) that have allowed achievement of sustainable management objectives (Large et al. 2013).

The overlap between fisheries surveys and current and potential wind energy lease areas on the U.S. Northeast continental shelf is significant (Figure 1). It is anticipated that 13 fisheries surveys will be affected by current offshore wind energy development (Hare et al. 2022). These offshore wind energy lease areas have the potential to impact biomass-based stock assessment surveys by excluding, limiting, or altering access by survey vessels to the lease areas, which has implications for the statistics that underlie the survey design (Methratta et al. 2020; Hare et al. 2022). As the footprint of offshore wind energy lease areas expands, the impact on the stock assessment surveys is anticipated to increase (Hare et al. 2022).

The fishery for Atlantic surfclams *Spisula solidissima* is particularly vulnerable to impacts from offshore wind energy development because of the overlap of its fishing grounds with lease areas (Kirkpatrick et al. 2017). Over US $1.5 million and $2.3 million worth of landed catch in the Atlantic surfclam fishery during 2018 and 2019, respectively, was caught in areas that are now leased for offshore wind energy (DePiper 2014; Benjamin et al. 2019). In addition, the Atlantic surfclam fishery uses gear (large hydraulic dredges) and vessels that are expected to be unable to effectively and safely fish within operational wind energy lease areas (Kirkpatrick et al. 2017). The Atlantic surfclam fishery is a key economic driver for communities from Virginia to Massachusetts, generating over $30 million (exvessel) in annual revenue. The Atlantic fishery has a long-term history of effective management, consistently meeting Magnuson–Stevens Fishery Conservation and Management Act goals related to overfishing and the state of being overfished (NEFSC 2022). Additionally, the Marine Stewardship Council has certified the Atlantic surfclam fishery as meeting requirements for a well-managed and sustainable fishery (DeAlteris and Allen 2016).

The Atlantic surfclam stock assessment is sensitive to survey constraints, including uncertainty imposed by limitations in the ability to survey the entire stock. The overlap of the federal Atlantic surfclam assessment survey strata and offshore wind energy lease areas may require modification to the survey design and could make some stock areas inaccessible to the survey because of vessel handling limitations, safety requirements, and assessment protocols (Methratta et al. 2020). Changes to existing survey procedures or interruption of the long-term survey time series can increase uncertainty in the biomass estimates that are used in setting fishery quotas, which in turn could lead to unintentional underharvest or overharvest, with consequent indirect impacts on the Atlantic surfclam stock and fishery. Additionally, increased uncertainty increases the precautionary buffers that are used in setting annual catch limits, which in turn decreases annual quotas (U.S. Sustainable Fisheries Act 1996).

The objective of this study was to evaluate the impact of excluding the federal assessment survey from wind energy lease areas on the Atlantic surfclam population

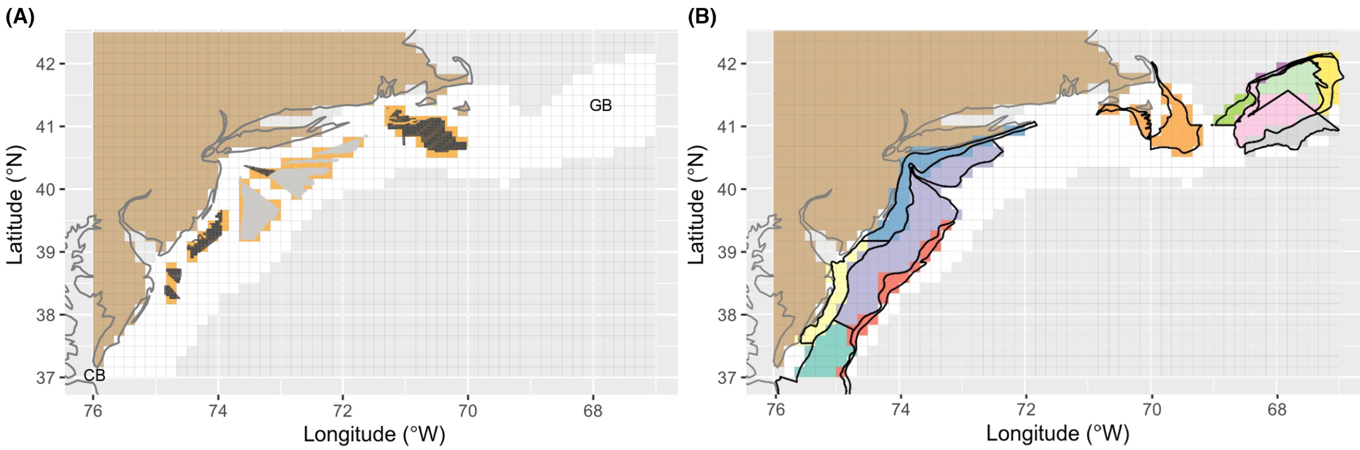

FIGURE 1. **(A)** Map of the U.S. Northeast continental shelf, showing the model domain that extends from Georges Bank (GB) to Chesapeake Bay (CB), existing offshore wind energy lease areas (dark gray), and potential wind energy lease areas (i.e., call areas; light gray). Model grid cells that were considered land (tan), grid cells within the biological domain (white), and grid cells in which fishing and survey vessel behavioral restrictions were imposed in wind energy lease areas (orange shading under wind energy lease area polygons) are indicated. **(B)** Correspondence between the Northeast Fisheries Science Center's Atlantic surfclam survey strata (color shading, outlined in black) and the model grid is shown. Details of the stock assessment survey strata are provided by Jacobson and Hennen (2019).

biomass assessment by using simulations from a Spatially Explicit Fishery Economic Simulator (SEFES) that includes modules for simulating Atlantic surfclam population dynamics, fishery management decisions, fishing fleet structure and behavior, and fishery economics. This model simulated the displacement of the survey out of wind energy lease areas and the concurrent displacement of fishing effort from the same areas. Therefore, the simulations can reflect the collective changes to the assessment survey results and spatially dynamic changes to stock biology and fishing effort. Offshore wind energy development may displace the Atlantic surfclam survey effort, and the simulations provided the approximate magnitude of change in biological reference points (BRPs) arising from the overlap of offshore wind energy lease areas with the areas of Atlantic surfclam habitat in the existing scientific survey. Exclusion of survey operations can interrupt time series, affecting stock assessments by increasing uncertainty in estimates that are used to project fishery quotas.

METHODS

Federal Atlantic Surfclam Stock Assessment Survey

The Atlantic surfclam stock assessment survey implemented by the NMFS Northeast Fisheries Science Center (NEFSC) is based on predetermined shellfish strata and uses a random stratified design (Jacobson and Hennen 2019). The surfclam survey assessment time series began in 1982. Sampling gear (hydraulic clam dredge) and protocols were generally consistent through 2011, with Atlantic surfclam surveys occurring every 1–3 years (NEFSC 2017). In 2012, the survey platform changed to a 45-m commercial fishing vessel (F/V *Pursuit*) with a more efficient hydraulic dredge and sensors, allowing for decreased survey uncertainty (Jacobson and Hennen 2019).

Atlantic surfclams collected during the federal assessment surveys from standardized dredge tows are counted, and shell length is measured. Meat weight per tow is computed using shell length–meat weight relationships to convert the numbers of Atlantic surfclams from the survey catch to meat weight equivalents (Marzec et al. 2010). The resulting meat weight equivalents are input to the stock assessment model that is used to estimate stock biomass. Spawning stock biomass (SSB) is estimated from the total weight of all sexually mature Atlantic surfclams in the stock. Biological reference points are indicators that serve as metrics of stock status and are used to define safe levels of harvest (Collie and Gislason 2001). The BRPs that are used to set Atlantic surfclam allowable harvest levels are estimated from a target SSB (SSB_{Target}) and a threshold value ($SSB_{Threshold}$) that represents the minimum acceptable SSB as

$$SSB_{Target} = \frac{SSB_0}{2}, \quad (1)$$

$$SSB_{Threshold} = \frac{SSB_0}{4}, \quad (2)$$

where the unfished biomass (SSB_0) is set at 2,054,000 metric tons, SSB_{Target} is set at 1,027,000 metric tons, and $SSB_{Threshold}$ is 513,500 metric tons, as estimated using the Atlantic surfclam stock assessment model in 2020 (Hennen et al. 2018; NEFSC 2022).

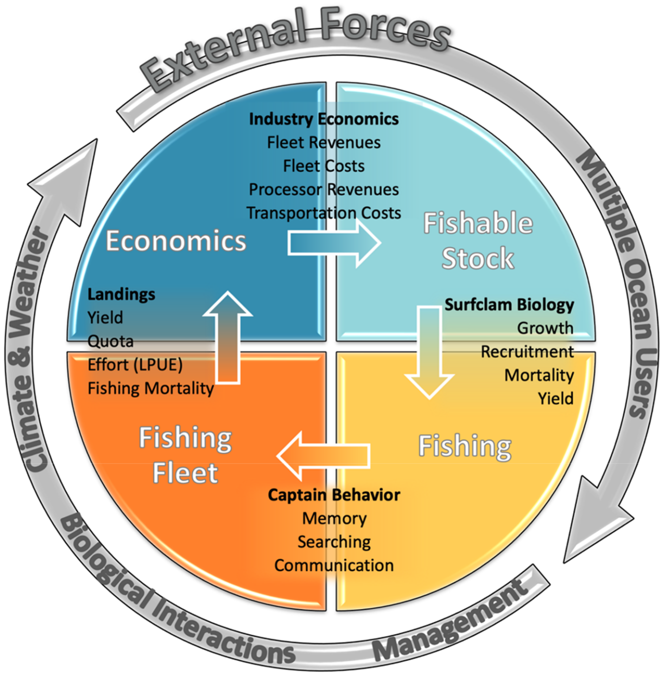

FIGURE 2. Components included in the Spatially Explicit Fishery Economic Simulator (SEFES) represent the fishable stock (light blue), fishing (yellow), fishing fleet (orange), and economics (dark blue). The primary processes that determine each component and links between components (inner arrows) and the external forces (outer arrows) that affect all model components (inner circle) are shown (LPUE = landings per unit effort). Full descriptions of SEFES are provided by Munroe et al. (2022) and Scheld et al. (2022). Figure is adapted from Munroe et al. (2022).

A second BRP examined was fishing mortality (F). The recommended F reference point, $F_{\text{Threshold}}$, is estimated as

$$F_{\text{Threshold}} = F^* \frac{F_{\text{MSY}}}{F^*_{\text{Max}}}, \quad (3)$$

where F^* is the fishing mortality rate (year^{-1}); F_{MSY} is the F at maximum sustainable yield (MSY) and was estimated as 0.12 year^{-1} using a management strategy evaluation model (Hennen et al. 2018); and F^*_{Max} is the highest average F observed in the fishery during a period of stable high biomass (1982–2015) and is specified as 0.03 year^{-1} (Hennen et al. 2018; NEFSC 2022).

Model Overview

The SEFES modeling framework consists of linked modules that simulate the Atlantic surfclam biomass, the fishing behavior (captain memory, communication, searching), and the fishing fleet (vessel characteristics, dispersion; Figure 2). Data from the Atlantic surfclam stock assessment surveys and management council, fishery-dependent data, and guidance from Atlantic surfclam industry and management representatives provided inputs for the development and implementation of SEFES as well as for verification of simulations (Munroe et al. 2022). Details of the SEFES model framework are provided by Munroe et al. (2022), and Scheld et al. (2022) provide details of the economic analyses used to assess the fishing fleet and processor operations. Previous implementations of SEFES were 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; Stromp et al. 2023, this themed issue). Assessment of the skill of simulations implemented with SEFES using a variety of fishery-independent and fishery-dependent data showed that the model provides a reasonable representation of the existing fishery (e.g., Munroe et al. 2022).

Implementation of SEFES

The spatial domain used for implementation of SEFES includes the continental shelf of the U.S. East Coast and extends from Georges Bank to Chesapeake Bay (Figure 1A). Wind energy lease areas and potential wind energy lease areas (the latter known as "call areas") have been defined by the Bureau of Ocean Energy Management (BOEM 2020b; Figure 1A). The wind energy call areas represent suitable areas that may be considered for future leasing for wind energy development. The call areas are designated during the planning stages to gauge specific interest in these areas. However, call areas are often reduced in size before they are designated as wind energy lease areas due to conflicts arising during public comments or due to a lack of interest from commercial developers. The model domain is configured using a grid of 10-min-latitude × 10-min-longitude cells, referred to as "ten-minute squares" (TMSs). The footprints of the wind energy lease areas do not align perfectly with the boundaries of individual TMSs. Therefore, a wind energy lease area was assigned to a TMS if the polygons defining the lease area or potential wind energy lease area, including a 3.704-km (2-nautical-mile) buffer, overlapped with 50% or more of a TMS (Figure 1A).

Management Approach

Fishery management, which is based on population size and stock biomass distribution from the federal Atlantic surfclam stock survey, provides an external forcing that modifies interactions within and among the SEFES modules. An annual survey of the simulated Atlantic surfclam stock biomass occurs in October of each year. The simulated survey provides estimates of Atlantic surfclam biomass and abundance. The distribution of the survey strata in the model domain follows the federal assessment survey as defined by Jacobson and Hennen (2019). The TMSs in the model domain with areas that overlapped more than 25% of the area within a given Atlantic surfclam survey stratum were assigned to that survey stratum (Figure 1B). The survey was based on tows distributed throughout the simulated Atlantic surfclam stock in a stratified random design. The simulated survey uses the Atlantic surfclam density for each TMS and samples every TMS in the domain. The abundance estimate assumed the same uncertainty as the federal Atlantic surfclam survey (coefficient of variation = 0.24; NEFSC 2022).

The federal assessment survey is the basis for setting the annual Atlantic surfclam quota based on a quota cap established by the fishery management plan (MAFMC 1986), the BRPs established in NEFSC (2017), and typical allowable biological catch (ABC) control rules. Annual catch limits cannot exceed the ABC; if it is exceeded, then fishing stops for the remainder of the year. However, the fishery operates under a quota cap of 3.5 million bushels of Atlantic surfclams that is imposed by the fishery management plan (MAFMC 2020), which the simulated SEFES catch never exceeds. Thus, the ABC does not affect the simulated fishery, as is true in the actual fishery. Calculation of the simulated ABC provides verification that the simulated catch is within the specified quota cap. The simulated survey also provides a biomass estimate similar to what is obtained under current survey conditions (Munroe et al. 2022).

Simulated tows were allocated to survey strata to acquire approximately 150 stations for a survey. However, the federal assessment survey is unlikely to be able to operate within wind energy lease areas because of safety and vessel handling restrictions (Methratta et al. 2020). Therefore, TMSs that include wind energy lease areas were excluded from the simulated annual assessment survey. Excluding these areas also reduced the area available for estimating the simulated Atlantic surfclam stock biomass. The inclusion of wind energy call areas increased the spatial footprint of offshore wind energy development by about 106%, effectively doubling the area in the simulations with imposed fishery and survey restrictions.

Simulations

Three scenarios were simulated to assess potential impacts of offshore wind energy development on the Atlantic surfclam stock assessment. The first scenario included no restrictions on survey vessel access or fishing activity in wind energy lease areas. This simulation provided a baseline for assessing the effect of restrictions in wind energy lease areas on the stock survey. The second scenario excluded survey vessel operation and fishing in current wind energy lease areas. The third scenario excluded survey vessel operation and fishing in current wind energy lease areas and in wind energy call areas. The simulations do not account for habitat loss due to other wind farm infrastructure, such as submerged cables (array or export) and scour protection. The model assumes that impact-producing factors caused by wind energy development, such as habitat modification, modified hydrodynamics, and changes in predation due to reef effects, will not affect the distribution and abundance of Atlantic surfclams.

Each scenario consisted of a set of 200 simulations, with each simulation run for 300 years. The first 100 years of a simulation included no fishing, which allowed the Atlantic surfclam population to reach a stable equilibrium. Fishing was enabled in the second 100 years of the simulation without wind energy lease area restrictions to allow fishery dynamics to come into equilibrium with the fishable biomass. The conditions specific to each scenario were imposed in the last 100 years of the simulation. The last 50 years of the simulation were used for analysis. This period represents a stable realization of the Atlantic surfclam fishery because the population biomass is adjusted to fishing pressure and associated random variability, which was introduced by weather restrictions, captains' choices regarding fishing locations, variability in recruitment, and wind energy lease area restrictions in the relevant simulations, as discussed by Munroe et al. (2022) and Scheld et al. (2022).

Atlantic surfclam biomass initialization.— Implementation of the Atlantic surfclam population dynamics model was based on data and observations that describe the current conditions (2016–2019) of the stock and fishery (Munroe et al. 2022). Initialization of the population dynamics model with current conditions allowed the simulations to reflect the current stock, preventing introduction of bias by the shift in Atlantic surfclam range over recent decades (Hennen et al. 2018; Hofmann et al. 2018).

Atlantic surfclam biomass calculation.— Atlantic surfclam biomass was calculated from the simulations to provide a total stock biomass for each year. This total fishable biomass (shell length > 120 mm) was derived outside of the survey to allow for examination of the fishable biomass throughout the whole stock (including biomass in wind energy lease areas that cannot be surveyed) under conditions of fishing restrictions.

A shell length–meat weight relationship was used to convert the number of Atlantic surfclams from the survey catches to meat weight equivalents (NEFSC 2022), which are used in the stock assessment models to estimate stock biomass. The Atlantic surfclam population dynamics model uses 18 length-classes, specified at 10-mm intervals between 20 and 200 mm. The average length for a category is the average of the lengths on either edge of the length-class (Munroe et al. 2022). The average wet weight (W; g) for Atlantic surfclams was obtained from an allometric relationship of the form

$$W = aL^b, \tag{4}$$

using the average length (L; mm) for each size-category. The values of the allometric parameters ($a = 5.84 \times 10^{-6}$ g/mm; $b = 3.098$) were from Marzec et al. (2010). The length data obtained from the simulated stock surveys were used to estimate wet weight, which was used to estimate Atlantic surfclam stock biomass.

Percent change in the total simulated biomass (outside of the survey), C_{Wn}, was calculated for simulations that included survey exclusion from existing wind energy lease areas (W1) or survey exclusion from existing lease areas plus call areas (W2) relative to the scenario in which the survey had unrestricted access to wind energy lease areas (W0) as

$$C_{Wn} = \frac{(\text{Biomass}_{Wn} - \text{Biomass}_{\text{ref}})}{\text{Biomass}_{\text{ref}}}, n = 1, 2, \quad (5)$$

where Biomass_{Wn} is the fishable biomass from each simulation in which the survey was excluded from existing wind energy lease areas and call areas (n = simulation W1, W2) and $\text{Biomass}_{\text{ref}}$ is the fishable biomass from the reference simulation that included no survey restrictions in wind energy lease areas.

The percent change in SSB estimated from the simulated survey ($C_{Wn\text{SSB}}$) was calculated for both wind energy lease simulations relative to the W0 scenario as

$$C_{Wn\text{SSB}} = \frac{(\text{SSB}_{Wn} - \text{SSB}_{\text{ref}})}{\text{SSB}_{\text{ref}}}, n = 1, 2, \quad (6)$$

where SSB_{Wn} is the SSB from the simulations involving exclusion of the survey from wind energy leases (n = simulation W1, W2) and SSB_{ref} is the SSB from the reference simulation that included no restrictions to the simulated survey in wind energy lease areas.

The calculated percent change in SSB for both simulations was then applied to the observed SSB from the most recent Atlantic surfclam stock assessment. Applying these percent changes to the observed SSB scales the observed SSB relative to lost survey opportunity due to exclusion from wind energy lease areas and displaced fishing effort. The adjusted SSB ($\text{SSB}_{\text{Adj}Wn}$), which represents the current SSB adjusted for the simulated loss of biomass, was calculated as

$$\text{SSB}_{\text{Adj}Wn} = \text{SSB}_{\text{Obs}} - (\lvert C_{Wn\text{SSB}} \rvert \times \text{SSB}_{\text{Obs}}), n = 1, 2, \quad (7)$$

where SSB_{Obs} is the observed SSB obtained from the federal assessment survey, which is set at 1,222,000 metric tons, the SSB that was estimated in 2020 (NEFSC 2022); and $C_{Wn\text{SSB}}$ is from equation (6).

The SSB at MSY for the simulations that excluded the survey from wind energy lease areas ($\text{SSB}_{Wn\text{MSY}}$) was then calculated as

$$\text{SSB}_{Wn\text{MSY}} = \frac{\text{SSB}_{\text{Adj}Wn}}{\text{SSB}_{\text{Threshold}}}, n = 1, 2, \quad (8)$$

where $\text{SSB}_{\text{Adj}Wn}$ is from equation (7) and $\text{SSB}_{\text{Threshold}}$ is set at 513,500 metric tons (NEFSC 2022).

Fishing mortality.— The simulated Atlantic surfclam fishing fleet was configured to represent the range of vessels and capacity in the present-day fishery (Munroe et al. 2022). The simulated fleet consists of 33 fishing vessels, each with individual specifications (i.e., dredge width, catch capacity, home port location, etc.). Atlantic surfclams are caught with a hydraulic dredge at a rate (cages/h; capped at 10 cages/h) that scales with the density of the simulated market-size Atlantic surfclams in each TMS. The simulated catch from the fishery is apportioned into standardized cages, which are converted to bushels of Atlantic surfclams (Table 1). Catch was defined as the sum of simulated landings plus 12% to account for incidental fishing mortality (NEFSC 2022). Simulated catch for each wind energy lease area scenario was estimated and converted from bushels to metric tons (Table 1).

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

$$F_{Wn} = \frac{\text{Catch}_{Wn}}{\text{Biomass}_{Wn}}, n = 1, 2. \quad (9)$$

The adjusted F ($F_{\text{Adj}Wn}$) was then estimated for each wind energy lease area simulation as

$$F_{\text{Adj}Wn} = F_{\text{Obs}} + \left[\left(\frac{F_{Wn} - F_{\text{ref}}}{F_{\text{ref}}}\right) \times F_{\text{Obs}}\right], n = 1, 2, \quad (10)$$

where F_{Obs} is the observed fishing mortality of 0.036 year^{-1} obtained from NEFSC (2022), F_{Wn} is from equation (9), and F_{ref} is the fishing mortality obtained from the reference simulation that included no restrictions on the survey.

The F that allows MSY ($F_{Wn\text{MSY}}$) was calculated from the simulations that excluded the survey from wind energy lease areas as

$$F_{Wn\text{MSY}} = \frac{F_{\text{Adj}Wn}}{F_{\text{Threshold}}}, n = 1, 2, \quad (11)$$

TABLE 1. Atlantic surfclam conversion factors for catch (modified from NEFSC 2022).

Unit	Equivalent
1 cage	32 bushels
1 bushel	17 lb meat
1 metric ton	2,204.6 lb (130 bushels)

where $F_{\mathrm{Adj}\,Wn}$ is from equation (10) and $F_{\mathrm{Threshold}}$ is set at 0.141 year^{-1} (NEFSC 2022).

RESULTS

Atlantic Surfclam Biomass

The mean simulated fishable biomass of Atlantic surfclams estimated from the SEFES reference simulation with unrestricted access to the wind energy lease areas (W0) was 585,000 metric tons. Relative to this value, the mean fishable biomass from the simulations that excluded fishing from current wind energy lease areas (W1) and from current lease areas and call areas (W2) increased by 0.34% and 1.20%, respectively (Figure 3). The exclusion of the fishery from the wind energy lease areas resulted in displacement of the simulated fishing effort to areas outside of the lease sites, producing a decline in catch and an increase in simulated biomass.

Exclusion of the simulated surveys from the current wind energy lease areas and from current lease areas and call areas resulted in decreases in simulated SSB of 3.5% and 17.3% respectively, relative to the reference simulation with unrestricted access. Adjusting the observed SSB of 1,222,000 metric tons (NEFSC 2022) to reflect these decreases yielded SSB losses of 43,100 and 211,400 metric tons, respectively. The relative SSB was then calculated using the adjusted SSB, the ratio of the adjusted SSB to the reported $\mathrm{SSB}_{\mathrm{Threshold}}$ estimated in 2020 (NEFSC 2022), which showed that exclusion of the survey from the current wind energy lease areas allowed for achieving 114.8% of the Atlantic surfclam biomass target (NEFSC 2022; Figure 4). Exclusion of the survey from current wind energy lease areas and call areas resulted in an SSB that was 1.6% below the SSB target (NEFSC 2022; Figure 4).

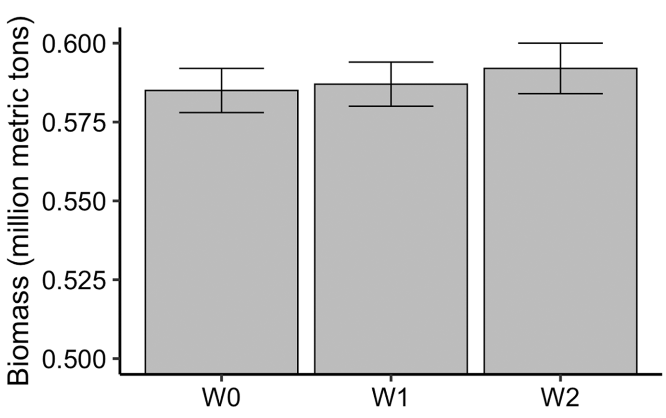

FIGURE 3. Total simulated fishable biomass of Atlantic surfclams obtained under conditions of unrestricted fishing (W0), exclusion of fishing from wind energy lease areas (W1), and exclusion of fishing from wind energy lease areas and potential wind energy lease areas (i.e., "call areas"; W2). Values are means across 10,000 observations from the final 50 years of simulations for a particular scenario. Error bars indicate ±1 SD.

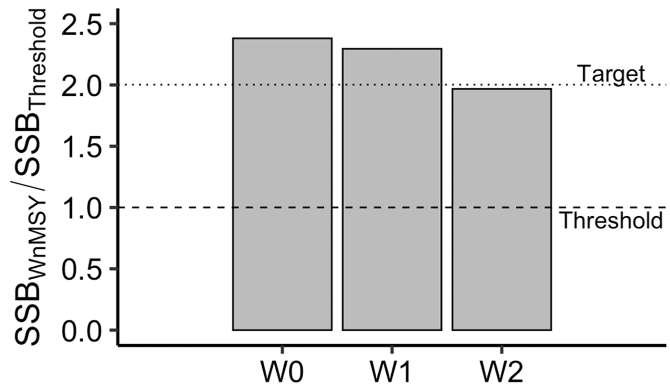

FIGURE 4. Simulated relative spawning stock biomass ($\mathrm{SSB}_{Wn\mathrm{MSY}}$/$\mathrm{SSB}_{\mathrm{Threshold}}$; see Methods) of Atlantic surfclams from the unrestricted survey in 2020 (W0; NEFSC 2022), simulated SSB when surveys were excluded from wind energy lease areas (W1), and simulated SSB when surveys were excluded from wind energy lease areas and potential wind energy lease areas (i.e., "call areas"; W2).

Fishing Mortality

The simulated Atlantic surfclam catch and biomass from the surveys decreased in response to restrictions on survey vessel operations in wind energy lease areas. Fishing mortality (catch/biomass) increased by 0.7% and 7.3% for the two lease area exclusion scenarios, respectively, relative to the reference simulation with unrestricted access. Adjusting the observed F (0.036 year^{-1}) to reflect these increases resulted in an increase in this rate by 0.0002 and 0.003 year^{-1}, respectively. Relative F, calculated as the ratio of the adjusted F to the reported $F_{\mathrm{Threshold}}$ estimated in 2020 (NEFSC 2022), increased in both of the simulated exclusion scenarios, remaining well below the overfishing threshold provided by NEFSC (2022). Therefore, neither simulated condition resulted in the occurrence of overfishing (Figure 5).

DISCUSSION

Effects of Restricting Access on Biomass Estimates

Offshore wind energy development will include infrastructure that could become obstacles resulting in de facto fishery and survey exclusion areas, potentially leading to fishing effort and catch displacement as well as changes to quotas or catch limits (Methratta et al. 2020; Scheld et al. 2022). Wind energy development plans in the United States do not automatically exclude competing use areas like fishing grounds, yet users such as commercial fisheries may be limited by other barriers (safety of navigation, lack of insurance, gear conflicts, etc.). It is anticipated that

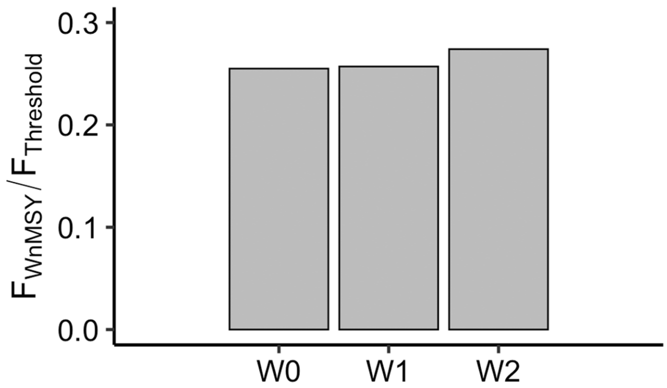

FIGURE 5. Relative fishing mortality ($F_{WnMSY}/F_{Threshold}$; see Methods) of Atlantic surfclams from the unrestricted survey in 2020 (W0), simulated F when surveys were excluded from wind energy lease areas (W1), and simulated F when surveys were excluded from wind energy lease areas and potential wind energy lease areas (i.e., "call areas"; W2).

the federal assessment survey, which uses a commercial Atlantic surfclam fishing vessel, will experience displacement from wind energy lease areas. The simulations suggest that this exclusion will result in approximately 3.5–17.3% of the Atlantic surfclam SSB becoming inaccessible to the survey and effectively removed from the fishery. Additionally, perceived F will increase by 0.7–7.3% due to the combined (1) reduction in observable stock biomass and (2) changes in catch caused by changes in fishing behavior. The decreased Atlantic surfclam biomass obtained from the survey and the associated uncertainty in stock estimates may trigger use of a precautionary approach that will impose more restrictive management measures.

Consistency in survey sampling and design is a key feature of federal fisheries surveys that allows evaluation of the status and trends of managed species over time (Hare et al. 2022). The inability to maintain the federal Atlantic surfclam assessment survey design and protocols will hinder the ability to accurately assess the stock. Changes to existing survey methodologies or disruption to the long-term survey time series will increase uncertainty in distribution, biological rates, biomass, and abundance estimates that are used to project fishery quotas. This uncertainty may lead to unintentional underharvest or overharvest of the Atlantic surfclam, with unintended and unexpected impacts on the stocks.

The simulated total fishable biomass of Atlantic surfclams increased nominally in the exclusion simulations because larger individuals remained in wind energy lease areas. However, these simulations do not account for habitat loss due to other infrastructure, such as subsurface cables and scour protection (i.e., large boulders, gravel, or cobble used to limit scour around turbine bases). Based on the number of hectares leased in 2021, approximately 708 ha of habitat could be lost across the Atlantic region of the U.S. Northeast due to the added scour protection needed to anchor wind energy turbines (a 12-MW turbine disturbs 0.34 ha; BOEM 2020a, 2021; ICF 2020). This loss of habitat would decrease overall Atlantic surfclam biomass within wind energy lease areas, making the simulated increase in overall biomass an overestimate of the actual changes that would result from offshore wind energy development.

Implications for Redesigning the Survey

Relocation of the Atlantic surfclam stock assessment survey will require new alternative sampling methods and statistical designs to maintain sampling accuracy and adapt data collection to offshore wind energy lease areas so as to reduce survey bias and uncertainty. Efforts are underway to develop new survey technologies, modified survey methods, and required calibrations that will minimize the impacts of offshore wind energy development on the quality of the federal assessment survey (Hare et al. 2022). The present analysis considered exclusion of Atlantic surfclam fishing by survey vessels using standard survey methods, fishing gear, and fishing vessels. Future studies should examine the impacts of this exclusion. The effect of changes in fishing gear and fishing vessel capability on the stratified design of the federal assessment surveys and setting of BRPs also remains to be considered in future studies.

Other sampling approaches for benthic fauna, such as grab samples or box cores, have proven to be insufficient replacements for sampling macrobenthic species such as Atlantic surfclams because those gears underestimate Atlantic surfclam abundance and biomass (Powell and Mann 2016; Powell et al. 2017).

Reduced survey effort within the wind energy lease areas is a possible modification that may allow some level of survey. Existing data from past federal, state, or independent surveys could be used to estimate an optimal minimum number of dredge stations that would sufficiently characterize Atlantic surfclam abundance and patchiness inside wind farm lease areas (Cochran 1977). A power analysis based on these existing data can provide guidance about expected variability and can indicate the sample number required to estimate overall Atlantic surfclam abundance (Munroe et al. 2023).

Exclusion of Atlantic surfclam fishing in wind energy lease areas does not imply that these areas can be considered as marine protected areas; this is because areas that are set aside for protection have specific criteria and design elements (Gaines et al. 2010). For example, species that experience limitations in local production due to fisheries might experience increases in biomass when fishing pressure is reduced or eliminated in wind energy lease areas (Lester et al. 2009). However, there is little evidence that Atlantic surfclams have a stock–recruitment relationship (Timbs et al. 2018). Hence, this stock is not presently limited by larval supply, and increased biomass resulting from maintenance of larger animals in wind energy lease areas may not necessarily lead to an increase in population abundance. The design criteria for wind energy lease areas in U.S. coastal waters, such as location, size, and configuration, are such that these regions do not function as conservation management tools that enhance fishery resources (Gaines et al. 2010; Gill et al. 2020). Furthermore, exclusion of fishing from these areas has effects that go beyond conservation. The redistribution of fishing effort to areas outside of wind energy lease areas potentially can result in localized overharvesting and competition for fishing grounds. For the Atlantic surfclam fishery, the combined effect of fishing exclusion and redistribution of fishing effort has consequences for the overall profitability of the fishery (Scheld et al. 2022).

Conclusions

Integrated fisheries models that recapitulate a single-species fishery survey and include realistic fishery dynamics and decision making, such as the model presented here, provide a basis for assessing the impacts of offshore wind energy development on scientific surveys that are designed to assess population biomass for a single species (e.g., the Atlantic surfclam). Offshore wind energy development may displace the Atlantic surfclam survey and fishing effort, resulting in propagation of uncertainty and limits on risk tolerance in management. Changes in BRPs driven by an inability to access the biomass within the wind energy lease areas have repercussions for management of the fishery resource. This first evaluation of the possible scale of impacts exerted by offshore wind energy development on a federally managed stock assessment survey can serve as the basis for future studies designed to examine the response of the Atlantic surfclam fishery to a nexus of simultaneous and complex natural and anthropogenic pressures as well as providing a framework for the development of similar models for other resources facing similar pressures. Understanding the impacts of fishery exclusion and fishing effort displacement from offshore wind energy development is critical to the sustainability of various fishing industries on the U.S. Northeast continental shelf.

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ORCID

Sarah Borsetti https://orcid.org/0000-0002-3985-0294

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