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Potential Future Impacts (2016–2055) of Offshore Wind Energy Development on the Atlantic Surfclam, *Spisula solidissima*, Fishery in the US Mid-Atlantic Bight Continental Shelf

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ABSTRACT

Offshore wind energy development on the Mid-Atlantic Bight (MAB) portion of the Northwestern Atlantic continental shelf could have adverse impacts on the future of the Atlantic surfclam, *Spisula solidissima*, fishery. The current and potential future areas designated for offshore wind energy development overlap with the present-day and projected Atlantic surfclam fishing grounds and so could limit the fishery. Fishery impacts imposed by displacement of fishing outside wind farm areas and possible restrictions on vessel transit through the wind farms were simulated using a spatially explicit fishery model. The distribution of catch, hours fished, landings per unit effort (LPUE), time at sea, fishing mortality, and the number of fishing trips were projected for five time periods encompassing the period of 2016–2055. Simulations showed a significant decline in the mean of all fishery metrics (apart from LPUE) as the area of wind farm restrictions increased in scale. Impacts were consistently larger when vessel transit through and fishing within offshore wind areas were prohibited. Impacts were also larger for MAB regions off New Jersey and Delmarva than regions farther north and east. These simulations highlight the necessity of evaluating future conditions as warming temperatures shift the surfclam range relative to the immobile wind farm locations. The offshore wind industry must consider projected long-term impacts of developmental expansion on surrounding sedentary benthic species and the commercially important fisheries that rely on them.

1 | Introduction

The offshore wind industry is expanding on the US northeastern continental shelf. The recent approval of the Coastal Virginia Offshore Wind (CVOW) project marks the fifth approved to date, keeping the United States on track with the goal of deploying 30 GW of offshore wind capacity by 2030 according to the US Department of Interior (BOEM 2023; DOI 2023). As renewable energy continues to look to the coastal ocean to increase capacity, competition within the blue economy for marine space and resources will also increase (Methratta et al. 2020; Munroe et al. 2022; Scheld et al. 2022; Borsetti et al. 2023; Methratta et al. 2023; Stromp, Scheld et al. 2023). A pivotal cog in the blue economy wheel for countless coastal communities across the nation is marine fisheries (McCay, Brandt, and Creed 2011; Young et al. 2019; Schupp et al. 2021; Guthrie et al. 2023). The planned expansion of offshore wind farm (OWF) development presents unique challenges for these overlapping industries.

Marine space is becoming increasingly limited as human activities in the ocean increase with advancements in technology. The potential for multiuse options rather than competitive interactions as different uses overlap (Schupp et al. 2019) has been proposed worldwide for OWF. Multiuse options have also been proposed for wave energy generation (Perez-Collazo, Greaves, and Iglesias 2015), marine protected areas (Kyriazi, Maes, and Degraer 2016), marine aquaculture (Buck et al. 2008), marine conservation (Lacroix and Pioch 2011; Kyriazi, Maes, and Degraer 2016), and even tourism (Piasecki et al. 2016). Indeed, the potential for offshore wind to coexist with fisheries in European seas has been considered (Kafas, 2017; Schupp and Buck 2017; Lukic, Zehden, and Ansong 2018). However, the geographic footprint occupied by commercial fisheries and OWF is similar with respect to depth range, proximity to coast, and sediment type, which raises concerns for the viability of the coexistence of fisheries and OWF worldwide (Kafas, 2017; Lukic, Zehden, and Ansong 2018). One project that has developed a multiuse case study combining OWF and fisheries is the Multi-Use in European Seas (MUSES) (Schupp and Buck 2017). Notwithstanding the multiuse issues raised by these studies, the development of hard-bottom communities on soft-bottom continental shelves consequent of wind turbine emplacement (Manoukian et al. 2010; Wilber, Carey, and Griffin 2018; Coolen et al. 2020a, 2020b; Mavraki, Degraer, and Vanaverbeke 2021) also provides the potential for expanding conflict and coexistence with a range of fisheries, commercial and recreational, as well as raising issues with respect to species of concern (Horne et al. 2021; Miles et al. 2021; Horwitz et al. 2022).

In the United States, only three commercial wind farms are producing power to date. The Block Island wind farm, located about 16 miles off the coast of Rhode Island, was the first and is composed of five turbines that have been operating since 2016 (ten Brink and Dalton 2018). Negative impacts from this wind farm have been highlighted by commercial fishers such as navigational concerns when transiting areas, reduced access, gear loss, and crowding (ten Brink and Dalton 2018). The CVOW project currently has two operational wind turbines located approximately 27 miles off the coast of Virginia Beach, with construction of 176 new wind turbines scheduled to begin in 2024 (BOEM 2021; Dominion Energy 2023). New York's first OWF, the South Fork Wind project, is currently under construction and comprises 12 turbines located 35 miles east of Montauk Point (South Fork Wind 2023). Twenty-five additional OWF projects are proposed to be underway by 2030, covering more than 2.3 million acres in the US Northeast alone (Methratta et al. 2023, 2020). A wide range of implications for marine ecosystems, marine fisheries, and coastal communities in the northeast region are foreseeable given the scale of offshore wind development.

Among the most exposed marine fisheries in the northeast to potential impacts from OWF development are those dependent upon sedentary shellfish, a preeminent example being the Atlantic surfclam (*Spisula solidissima*) fishery (Kirkpatrick et al. 2017a; Munroe et al. 2022; BOEM 2022a; Borsetti et al. 2023). The Atlantic surfclam fishery has an average annual revenue (ex-vessel) of over $30 million and produces over $1.3 billion in total economic impact when combined with the ocean quahog, *Arctica islandica*, fishery (Murray 2016). This fishery operates in the Mid-Atlantic Bight (MAB) and on Georges Bank with major ports located in Ocean City, MD; Atlantic City, NJ; Point Pleasant, NJ; and New Bedford, MA (Figure 1) (Munroe et al. 2022; Scheld et al. 2022). This species has a historical range from Cape Hatteras to Georges Bank and the extreme inshore

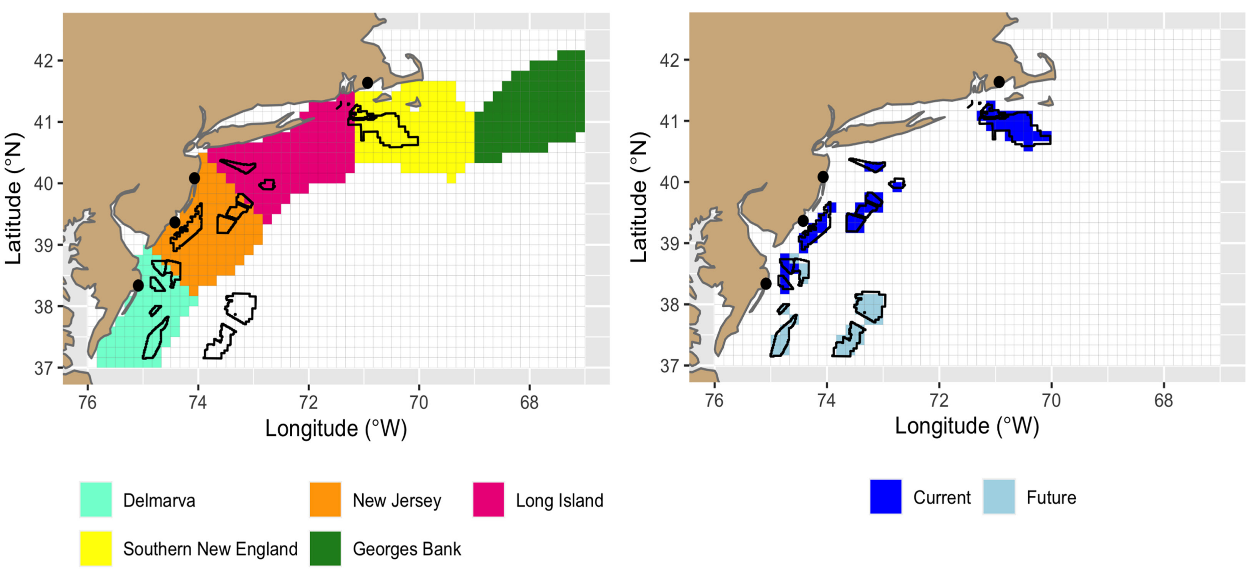

FIGURE 1 | A regional map of the Mid-Atlantic Bight with regions shown on the left as Delmarva (DE, MD, VA) shown in teal; New Jersey shown in orange; Long Island (NY) shown in pink; Southern New England (shown in yellow); and Georges Bank (shown in green). Black lines outline the locations of OFW areas, depicted more clearly in color on the right. Port locations are noted with black circles and include New Bedford, MA; Point Pleasant, NJ; Atlantic City, NJ; and Ocean City, MD. Established current wind farm leases (dark blue) and planned future wind farm leases (light blue) are shown on the right.

of the Gulf of Maine (Hofmann et al. 2018; Stromp, Scheld et al. 2023). This portion of the northeast continental shelf has experienced severe climate-induced warming that has resulted in range shifts of a variety of marine species (Lucey and Nye 2010; McClenachan et al. 2019; Young et al. 2019; Stromp, Powell, and Mann 2023; Spencer et al. Early View). The Atlantic surfclam is among the most sensitive species in the North Atlantic, with an upper optimal thermal limit of about 21°C, and rapidly suffers thermal stress above about 23°C (Munroe et al. 2013; Narváez et al. 2015) leading to starvation and death (Kim and Powell 2004). A northward and offshore shift in the Atlantic surfclam's range in response to the increase in bottom water temperature is well documented (Weinberg 2005; Hofmann et al. 2018; Timbs, Powell, and Mann 2019) and must be considered in the evaluation of interactions with OWF development over the coming half-century (Stromp, Scheld et al. 2023).

Obstacles to continued profitability for the Atlantic surfclam fishery go beyond OWF development as the species continues to shift north and offshore due to North Atlantic warming. Ecologic and economic fishery challenges are highlighted by Spencer et al. (Early View), Stromp, Scheld et al. (2023) and Stromp, Powell, and Mann (2023), Munroe et al. (2022), and Scheld et al. (2022) and include a progressive overlap in Atlantic surfclam habitat with ocean quahogs. Fishery regulations prohibit the landing of mixed catches. Currently, no time-efficient technology capable of sorting the two species on board the fishing vessel exists, and Stromp, Scheld et al. (2023) suggest that any mixture above 4% of ocean quahogs caught would limit fishing for surfclams. Consequently, the addition of wind farms constrains the fishery inshore by the limited fishing possible within wind turbine arrays and the overlap with ocean quahogs constrains the fishery offshore by limiting the fishing grounds available for economic access, together substantially limiting the availability of viable fishing grounds over a substantial portion of the continental shelf (Stromp, Scheld et al. 2023), an outcome potentially exacerbated as warming of the Northwestern Atlantic continues.

This study is designed to evaluate the potential future impacts of OWF on the Atlantic surfclam fishery, recognizing the anticipated continuing movement of the stock relative to the static footprint of OWF and the expanding overlap with ocean quahogs. Impacts were examined over the entire stock, within the stock, and in five MAB regions historically used for evaluation of the fishery. Performance of the resulting simulated fishery is compared among cases with OWF present and a no-wind-farm base case. To do so, a spatially explicit, agent-based modeling framework (Spatially Explicit Fishery Economics Simulator [SEFES]) is used to evaluate four scenarios that represent varying degrees of OWF buildout and the ability for vessels to transit through wind turbine arrays during selected time intervals from 2016–2019 to 2052–2055, during which warming temperatures continuously modify the spatial distribution of the Atlantic surfclam.

2 | Methods

To anticipate future fishery responses in the changing MAB landscape, quantitative assessments of the overlap between OWF development and the Atlantic surfclam fishery were implemented using the SEFES modeling framework originally described by Powell et al. (2015) (see also Kuykendall et al. 2017, 2019). Spencer et al. (Early View, Early View) discuss simulations projecting trends in the Atlantic surfclam stock and fishery responsive to climate-induced warming, including the expanding overlap with ocean quahogs constraining economically viable fishing grounds. Stromp, Scheld et al. (2023) evaluate the interactive impacts of wind farms and the overlap of surfclams onto ocean quahog habitat in the present-day fishery, based on earlier analyses also using SEFES by Munroe et al. (2022) and Scheld et al. (2022). These publications provide the basis for the present implementation of SEFES to evaluate future trends in the fishery relative to OWF and climate change.

The spatial domain used for this implementation of the SEFES model includes the US east-coast continental shelf from the Chesapeake Bay to Georges Bank. The domain is described using a 54 × 33 grid that consists of 10-min latitude by 10-min longitude squares (TMS). Within this domain five regions are designated that have been used historically to provide a regional perspective of the fishery (Spencer et al. Early View). These regions, starting in the south, are Delmarva encompassing northern Virginia, Delaware, and Maryland, New Jersey separated from Delmarva at Delaware Bay, Long Island, NY, separated from New Jersey at Hudson Canyon, Southern New England separated from Long Island at Block Island, and Georges Bank separated from Southern New England by the Great South Channel (Figure 1). Regional metrics presented hereafter refer to the stock and fishing effort within each region. Thus, as an example, regional fishing mortality rate is calculated using the biomass of the stock within that region and the landings produced by that region within the defined time period.

Spatial layers of current leases where wind farms can be positioned, and future planning areas were obtained from the Bureau of Ocean Energy Management (BOEM 2022b). Information on the most up-to-date areas under lease or leasing consideration within the US Outer Continental Shelf can be found at BOEM (2024b). Individual lease and planning area polygons were buffered (1 m) and joined to create individual polygons for contiguous leases and planning areas, which were then overlaid on the model grid (Figure 1). The proportion of grid cell overlap with lease and planning area polygons was calculated for each model grid cell. Catch predicted to be within current leases and future planning areas was calculated by multiplying average annual catch per model grid cell under the no wind scenario by the proportion of overlap with current leases and future planning areas and summing across model grid cells. Catch within OWF areas was divided by average annual total catch to assess the proportion of total catch predicted to occur in OWF areas during each time period considered.

The simulated fishing fleet is represented by 33 unique fishing vessels: These encompass the entirety of the US surfclam fleet fishing in federal waters. Each vessel is operated by captains with specified behaviors based on the degree of communication between captains within and between ports of call, the degree and frequency of searching, and the weighting of knowledge concerning LPUEs obtained from the memory of recent trips and trips taken at earlier times. These behavioral patterns are described in Powell et al. (2015) and Munroe et al. (2022). Vessel operations are also modified by limitations on LPUE imposed by the presence of more than 4% ocean quahogs in a dredge haul (Stromp, Scheld et al. 2023), trip occurrence and duration constraints due to inclement weather, and time-at-sea constraints consistent with fishery procedures (Stromp, Powell, and Mann 2023; Munroe et al. 2022; Scheld et al. 2022). Vessel routes to chosen fishing grounds follow a direct line path unless obstacles exist due to the presence of land in that direct line or due to an imposed limitation to vessel transit through wind farm arrays. In these cases, the shortest path for a vessel to travel from its port to a TMS for fishing is calculated with the A* (A-star) algorithm that uses a grid of points as possible waypoints for travel. Some points in the grid are blocked either because they are on land or because they are in a wind farm that does not allow passage. Because of the regular grid of points, the path is not unique. However, the distance determined by the algorithm is the shortest and is the same for all paths found by A* (Hart, Nilsson, and Raphael 1968; Premakumar 2024).

Simulations were run to assess the possible future impacts of OWF development on the Atlantic surfclam fishery using four sets of scenarios for fleetwide and regional comparisons set in five time periods between 2016 and 2055. Each scenario was run for cases based on projected 4-year averaged bottom water temperatures from 2016 to 2019 (hereafter 1619), 2026 to 2029 (2629), 2036 to 2039 (3639), 2046 to 2049 (4649), and 2052 to 2055 (5255). The 4-year time block was dictated by the 2016–2019 time block used for verification by Spencer et al. (Early View). The four scenarios distinguish two OWF development states and two vessel operational assumptions, which are as follows: No transit allowed through established leases, no transit allowed through established and planned future leases, transit allowed through established leases, and transit allowed through established and planned future leases. Grid cells for OWF lease and planning areas were determined with a 50% overlap within polygons (>=50% overlap with lease/planning area polygons, including a 2-km buffer). Fishing within OWF arrays is not allowed in any simulation. Performance metrics include catch (=landings as discarding does not occur in this fishery) in cages yr^{-1} (1 cage = 32 surfclam bushels; 1 surfclam bushel = 53.2 L), hours fishing ($hr\,yr^{-1}$), landings per unit effort (LPUE) in cages hr^{-1}, number of yearly trips, days-at-sea ($d\,yr^{-1}$), and fishing mortality rate (yr^{-1}). The mean of each fishery metric for each OWF-transit scenario was then compared to the mean of a scenario where no OWF were present. For simulation structure, see Spencer et al. (Early View).

The results are presented as the difference in mean values for each fishing metric obtained by subtracting the OWF value from the mean value in the absence of OWF. For ease of comparison between figures, apart from some fleetwide metrics in Figure 2, the y-axis scale is held constant between figures for each metric. Thus, for example, for variations in LPUE, the y-axis of all figures is −0.6 to 0.6, regardless of the range of the data within a particular figure. Supporting data are provided in Supporting Information.

3 | Results

3.1 | Fleetwide Trends

Focusing first on the entire fleet, simulations showed that fishing activity metrics varied with different OWF restrictions (Table S1 and Figure 2). For each OWF scenario, from 1619 to 5255, mean catch declined for each case when compared to the same period without OWF. The largest differential between an OWF case and the no-OWF base case in most fishery metrics was observed for the OWF scenario that included both ongoing and planned future OWF buildouts for which vessel transit was not allowed. These differentials are similar for each time period within each of the fishing metrics including catch, hours fishing, trips, days at sea, and fishing mortality rate.

For catch, time at sea, number of trips, hours fishing, and fishing mortality rate, the differential between the OWF scenario and the no-OWF base case increased with increasing acreage committed to OWF and with increased restrictions on vessel operation (Figure 2). The most extreme case was consistent with present and planned future OWF coupled with an inhibition on vessel transit. The exception was LPUE, which changed modestly across all cases (Figure 2).

The proportion of total catch from the no-OWF scenario occurring in existing leases and future planning areas fluctuated around 15% across time periods (Figure 3; see Figure 2 for fleetwide impacts). The proportion of catch in current lease areas was at its highest point during 2016–2019 at 13%, decreasing to 10% during 2036–2039, and then increasing slightly. The proportion of total catch occurring in future planning areas was at its lowest point during 2016–2019 at 3%, increasing to 6% during 2036–2039, and declining slightly thereafter.

3.2 | Regional Case Trends: Present vs. Future

Regionally, for all scenarios, transit or no transit, present-day or present-day plus planned future OWF, catch decreased by over 10,000 bushels in the 2629 case due to the loss of fishing grounds and impeded transit by OWF areas off New Jersey and Delmarva (Figure 4). Modest gains in catch occurred on Georges Bank, off Nantucket, and inshore off southern Delmarva (Figure 4). In the 5255 case, catch decreased by more than 10,000 bushels in the Southern New England and Delmarva areas as well as off New Jersey (Figure 4). Outside of the OWF areas, catch increased substantially on Georges Bank for the 5255 period, and sporadic locations inshore off Long Island, and offshore of leased regions off New Jersey and Delmarva consistent with the range expansion of the Atlantic surfclam documented by Spencer et al. (Early View) and the forced change in the geographic distribution of the fleet due to restriction in available fishing grounds and direct-line transit.

3.3 | Near-Present Case (2026–2029)

Spencer et al. (Early View) showed that the Atlantic surfclam stock is expected to reach a nadir in biomass during the 2629 period and then begin a multidecadal expansion through 5255 as the stock continues to expand offshore from New Jersey through Southern New England. Accordingly, these two time periods are compared with respect to the influence of OWF. For the 2629 period, metrics measuring fishing performance were negatively impacted by OWF, predominately in the New Jersey and Delmarva regions (Table S2 and Figure 5).

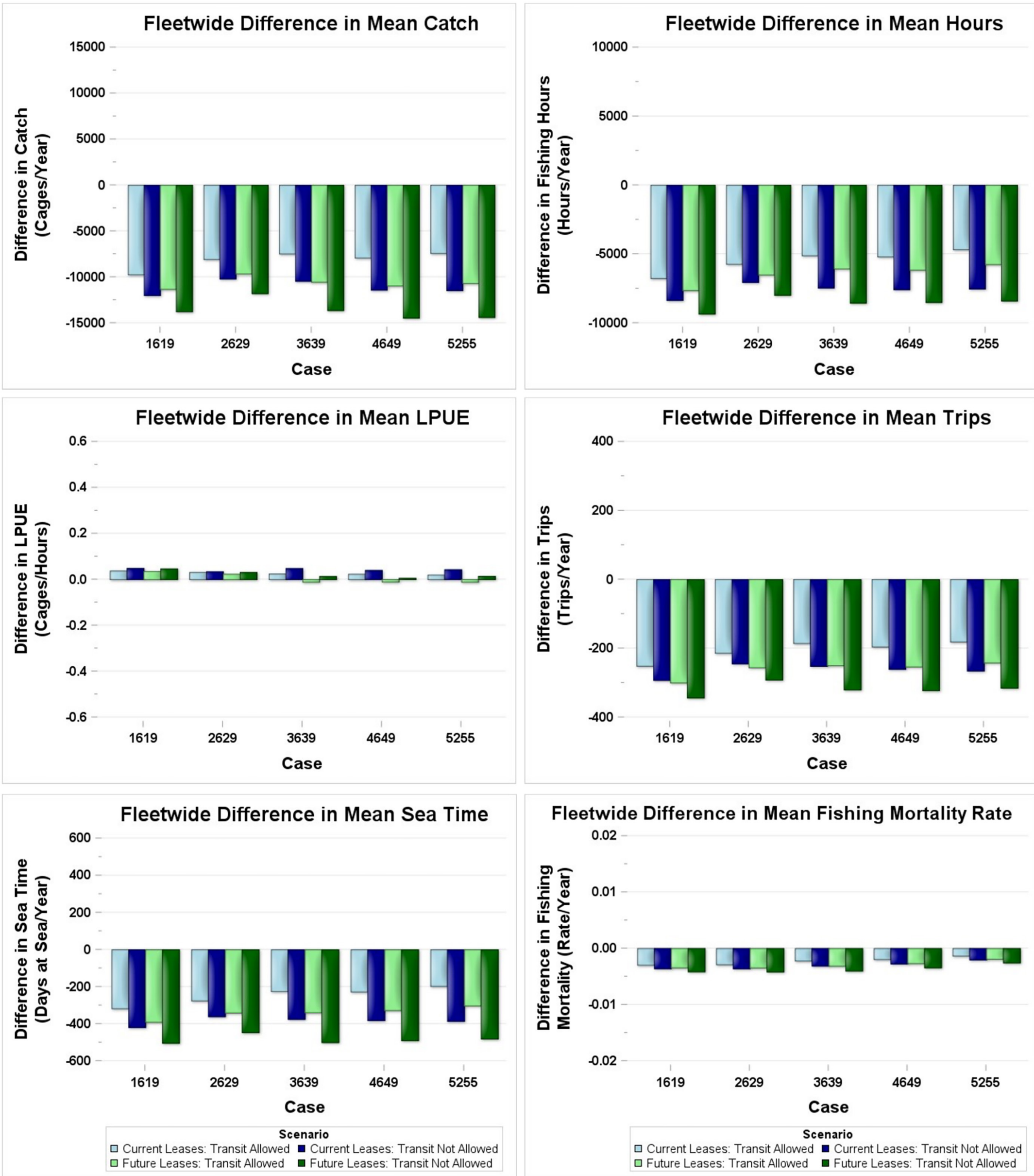

FIGURE 2 | Fleetwide fishing metrics calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario in the same time period: catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

The differentials in the mean catch, hours fishing, trips, and days at sea were consistently the greatest for the New Jersey region, followed by the Delmarva region. In comparison to the prominent differentials in OWF impact observed between these two regions and the remaining three, regardless of the degree of buildout or impeded vessel operations, the differentials within region between OWF-transit cases were minor. That is, whereas, on average, the no-transit cases showed greater impacts than the transit cases and the no-transit case with present-day and planned future OWF buildout showed the greatest impact within each region, these within-region differentials between the four OWF-transit scenarios were minor in comparison to the differentials observed for each of the four OWF-transit scenarios between regions. Thus, the differentials estimated at the scale of the entire fleet in fishery performance metrics such as catch (Figure 2) do not reflect the larger and smaller impacts of OWF recorded regionally (Figure 5).

3.4 | Future Case (2052–2055)

All fishing metrics for the Delmarva, New Jersey, and Southern New England regions declined in 5255, whereas in Long Island and Georges Bank, fishing metrics (apart from LPUE) increased across all OWF scenarios relative to the no-OWF case for that time period (Figure 6). Generally, increases in fishing metrics in the Long Island region accrued under present-day OWF development compared to the no-OWF case for the 5255 time period; these increases were somewhat muted when future OWF development was included. For Georges Bank, the best outcomes accrued when transit through wind turbine arrays was permitted; the tendency for a positive outcome was considerably mitigated when transit was disallowed. For Delmarva, the addition of planned future leases dramatically increased the negative impact on fishing performance metrics relative to other regions, an outcome also inferred from the distribution of the fishery shown in Figure 4.

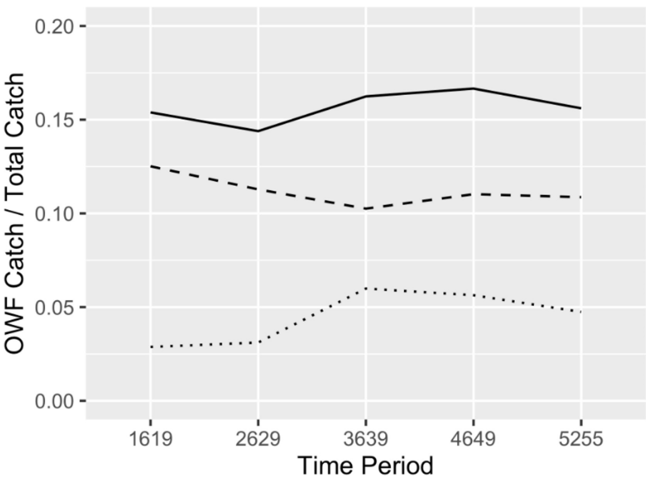

FIGURE 3 | Fraction of total catch under the no wind scenario for each time period occurring in current lease and future planning lease areas (solid line), current lease areas only (dashed line), and future planning areas only (dotted line).

3.5 | Area Trends

As the influence of OWF was largest in the New Jersey and Delmarva regions, results for these regions were compared between time periods (Figures 7 and 8; see also Table S2).

3.5.1 | New Jersey

For the New Jersey region, trends in catch, hours fishing, trips, and days at sea varied little between time periods (Figure 7). Generally, negative impacts on fishery performance with OWF development were modestly larger when vessel transit was not allowed, but the differentials between present-day and present-day plus planned future OWF were small. The addition of future OWF development did not influence these primary fishing metrics much under the planned buildout considered here. Greater variation was observed in fishing mortality rate, which reached the highest differential between simulations with and without OWF in 3639 and declined distinctly thereafter. The differential in LPUE with and without

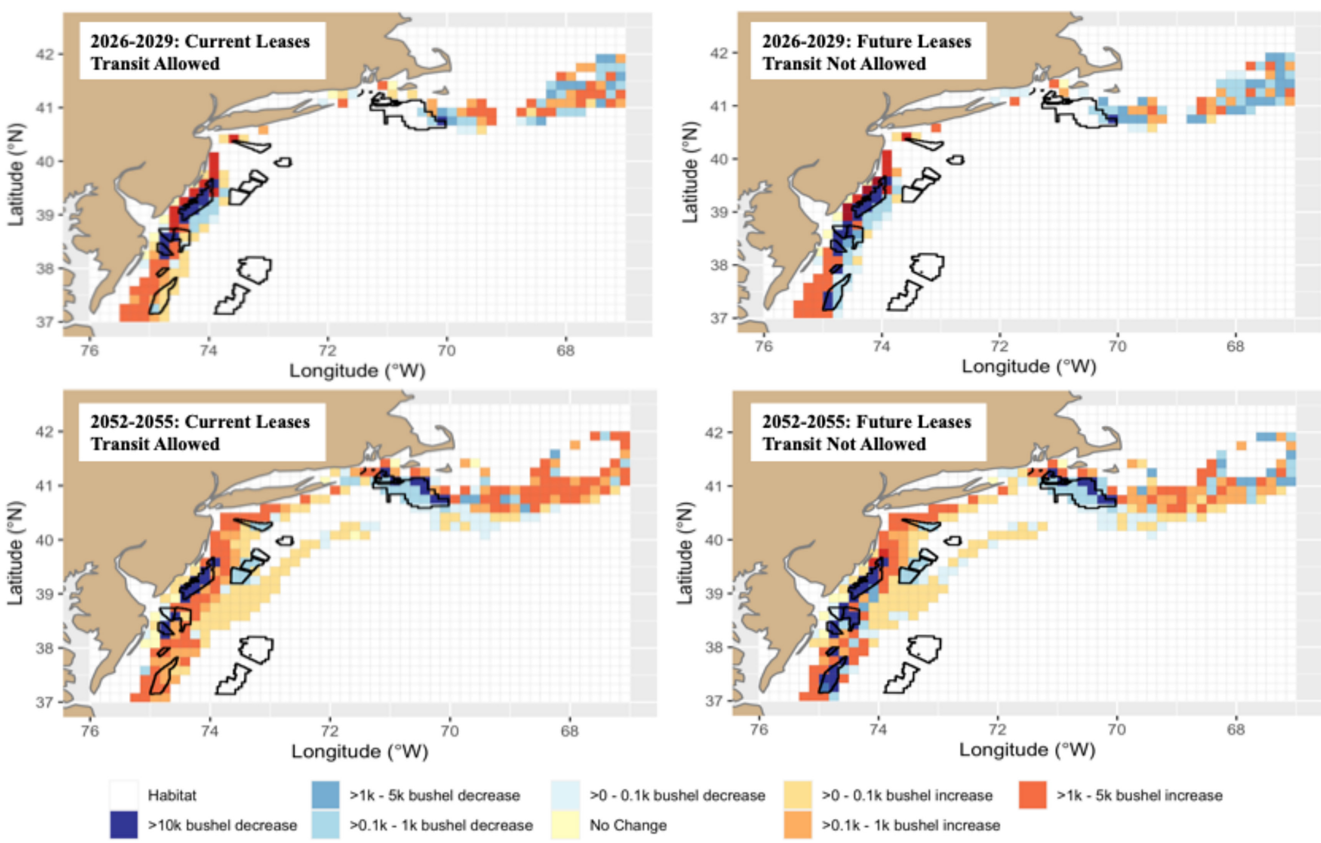

FIGURE 4 | Geographic distributions of changes in catch (cages per year) given in thousands of bushels (k) compared to the no OWF case for the same time period for cases 2629 and 5255 for transit allowed (left) and transit not allowed (right) scenarios. Dark blue represents the highest decrease (>10,000 bushels), whereas dark orange represents the highest increase (>1000–5000 bushels).

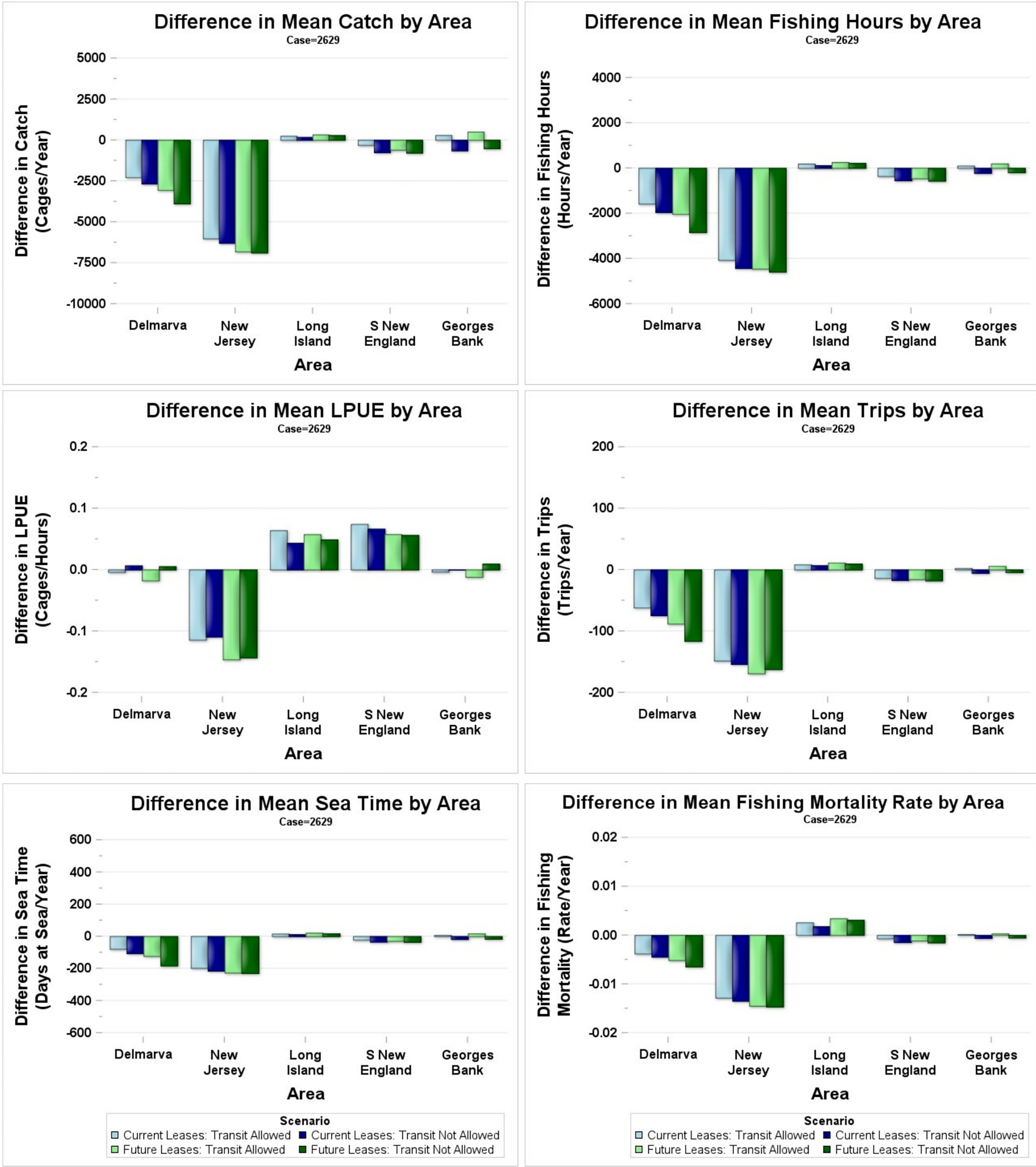

FIGURE 5 | Difference in fishing metrics for case 2629 calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

OWF, on the other hand, gradually declined over time from 1619 to 5255.

3.5.2 | Delmarva

Trends across time were considerably more variable for the Delmarva region in comparison to New Jersey (Figure 8 vs. Figure 7). The differential impact of the four OWF-transit scenarios on catch, hours fishing, trips, and days at sea varied similarly for each time period. However, the impact of OWF increased consistently in 3639 for cases that included planned future OWF for most fishing metrics in comparison to the other time periods (Figure 8). This trend was particularly clear for LPUE, days at sea, catch, and number of trips taken. Generally, negative outcomes with OWF development were modestly larger when vessel transit was not allowed, but this differential was minor compared to the impact of adding future OWF development to the ongoing OWF buildout present-day (also compare Figure 4). This contrasts with the outcomes projected for the New Jersey region.

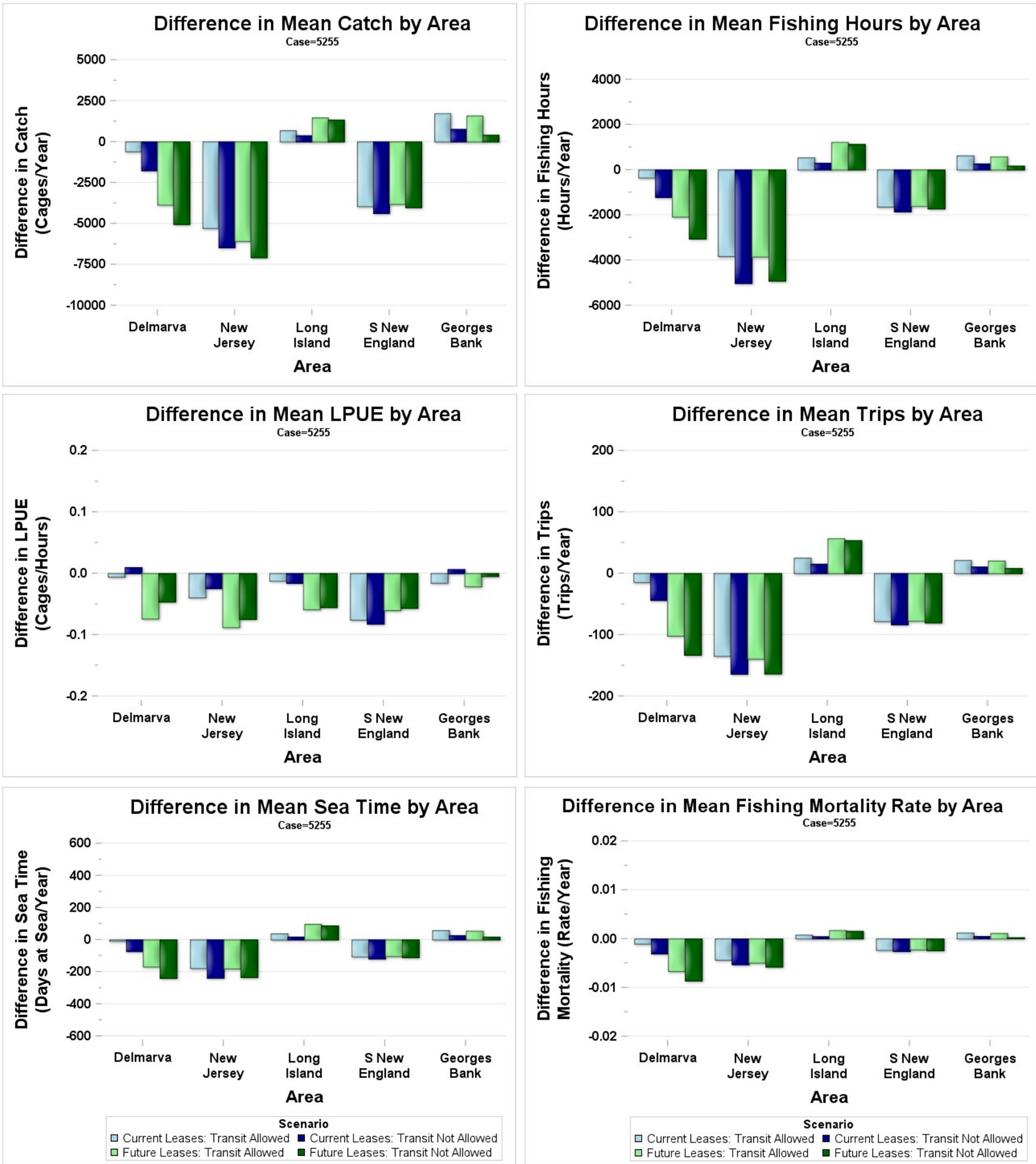

FIGURE 6 | Difference in fishing metrics for case 5255 calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr-1). Scenario legend applies for all metrics.

3.6 | Time Trends Relative to 1619: 2629 and 5255

The previous comparisons assume that the fishery perceives the differential between a future time with and without OWF, but the experience likely to be perceived is the difference between the near present-day case (1619) without OWF and the future case with OWF. Examination of results using this comparison shows that most fishery performance metrics were negatively impacted in 2629 relative to 1619 (Figures 9–12; also see Table S2). Differentials between the four OWF-transit options, regardless of the combination of transit allowed or not allowed and present or present plus planned future OWF, effectively showed the same differential. That is, the differences observed were primarily due to the differential distribution of surfclams between 1619 and 2629, not the status of OWF. Interestingly, the largest differentials in comparing the 2629 cases with and without OWF, present in New Jersey and Delmarva (Figure 5), were muted in the 2629 to 1619

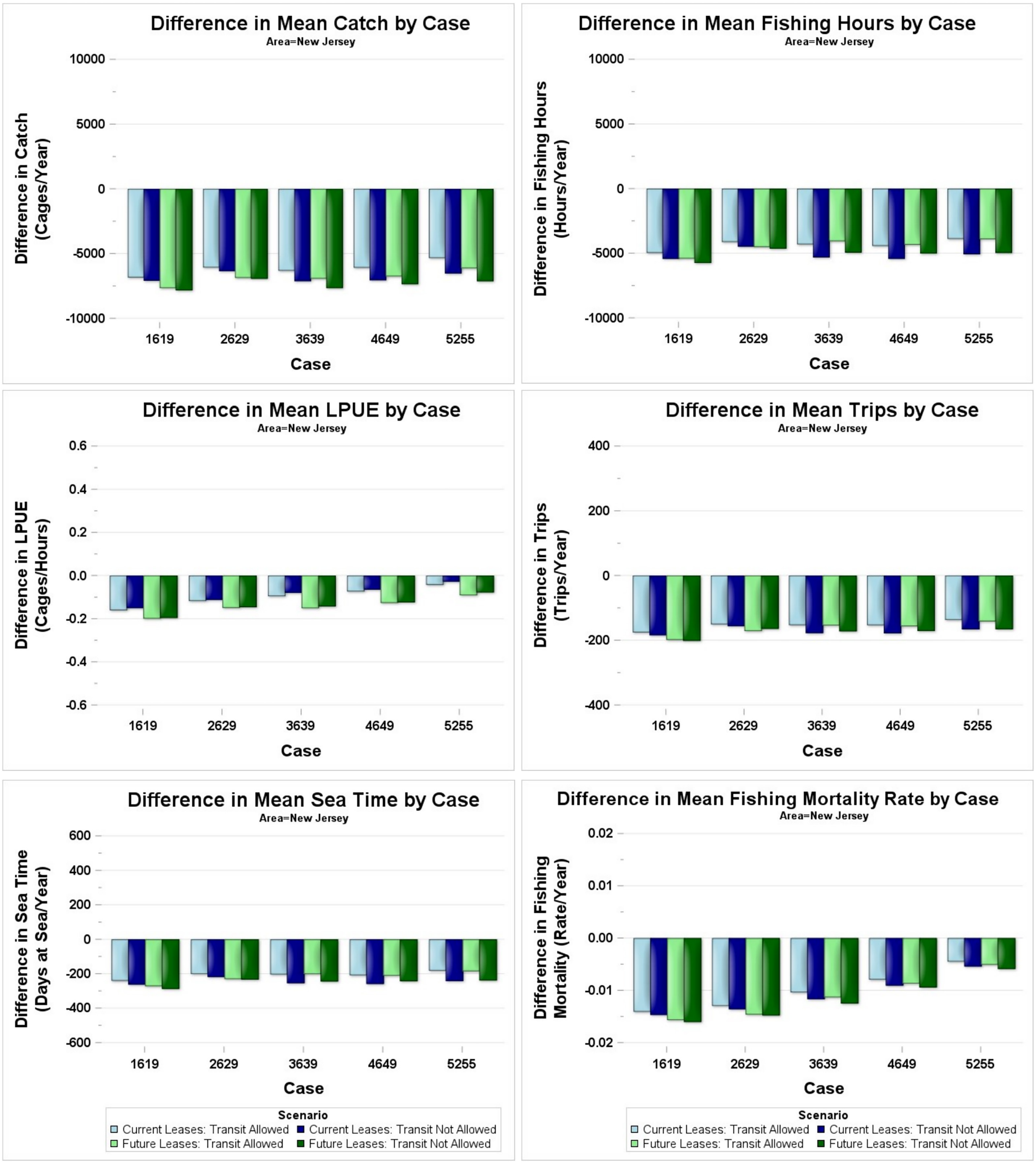

FIGURE 7 | Difference in fishing metrics for New Jersey area calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

comparison (Figure 9), suggesting that the shift in the geographic footprint of the species partially mitigated the impact of OWF in these two regions.

Although a few negative impacts of OWF in 5255 were still present (Figure 10) when fishery performance was compared to the 1619 case without OWF, the dominant trend was the improvement in fishery performance metrics relative to the within-time-period comparison of 5255 with and without OWF (Figure 6). LPUE increased in all regions, whereas fishing mortality rate decreased in all regions. Days at sea and hours fishing tended to decrease consistent with the increase in LPUE. Apart from the Long Island shelf, the number of trips declined, also consistent with an increase in LPUE. The positive response for the Long Island region reflects the increase in Atlantic surfclam biomass in that region by 5255 (Spencer et al. Early View). Once again, as in the 2629 comparison, the influence of the four OWF-transit options, transit or no transit, present or present plus planned future buildout, was minor in comparison to the influence of the biological expansion of the species.

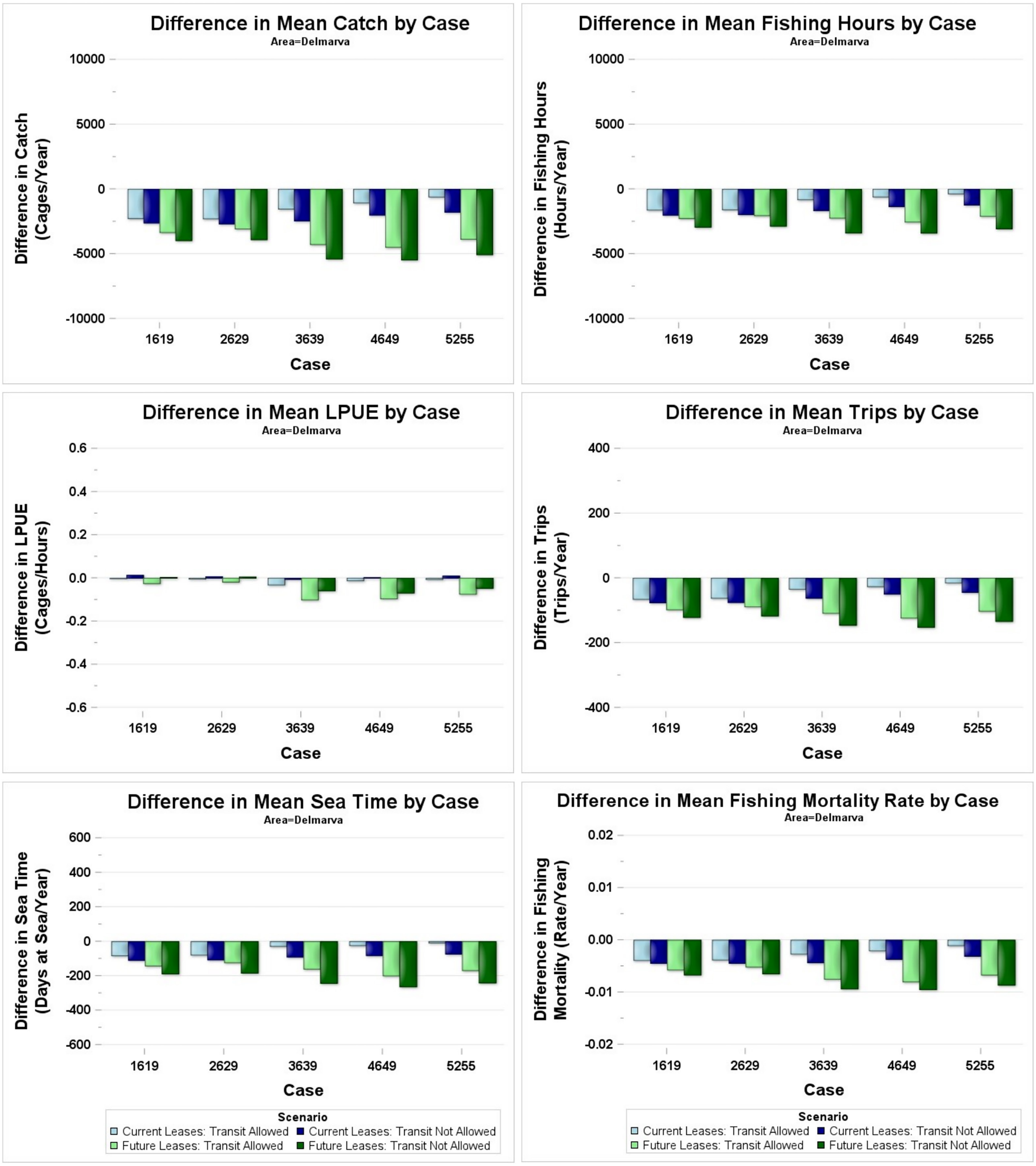

FIGURE 8 | Difference in fishing metrics for Delmarva area calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

3.7 | Area Trends Relative to 1619

3.7.1 | New Jersey

The influence of OWF in the New Jersey region was consistently muted when compared to the fishery performance of 1619 without OWF in contrast to the direct comparison between OWF and no-OWF during 2629 (compare Figure 11 to Figure 7). The impact of the four OWF-transit cases on fishery performance metrics trended from negative to positive from 2629 to 5255 for many metrics such as catch, days at sea, and LPUE. The distinctly different trend for fishing mortality rate acknowledges the lesser impact of the fishery on an increasing stock size. In fact, across all time periods, the negative impact of OWF, documented in the comparisons of fishing performance without OWF and with OWF within the same time period (Figures 2 and 5–8), was lessened or removed when the no-wind farm comparator was based on the fishery performance in 1619, showing the importance of the surfclam range expansion anticipated as warming of the Northwest Atlantic continues. This range shift substantively ameliorated the negative impact of OWF when compared to the fishery performance estimated for 1619 without OWF.

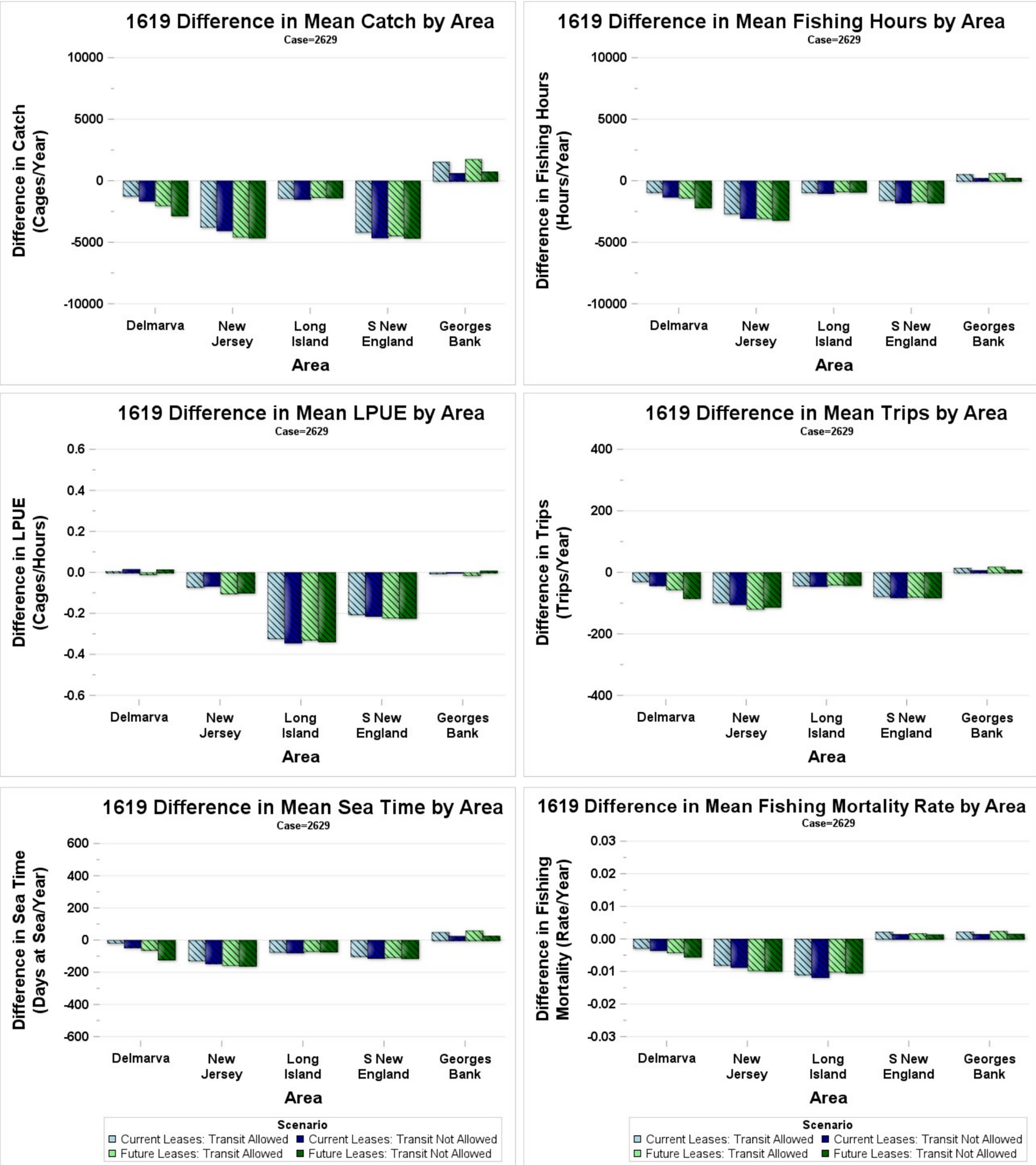

FIGURE 9 | Near-present day wind case 2629 compared to 1619 no wind case: the mean of each fishery metric and transit scenario are calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario in 1619 (Mean Wind-1619 Mean No Wind) for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

3.7.2 | Delmarva

The results for Delmarva generally followed those of New Jersey, though more chaotic (Figure 12) was the case with the within-time-period comparisons (Figure 8). However, unlike New Jersey, the larger impacts of the OWF transit cases comparing the present and planned future OWF to the present-day cases were clear and often dramatic. The Delmarva region is clearly more sensitive to the planned future buildout of OWF than other regions.

4 | Discussion

4.1 | Perspective

Plans for a clean energy future within the US continental shelf include BOEM's timeline to complete reviews of at least 16 OWF projects by 2025 (BOEM 2024a). An action plan was released by BOEM with little consideration for the potential impacts to fisheries (BOEM 2023). Kirkpatrick et al. (2017a, 2017b) did,

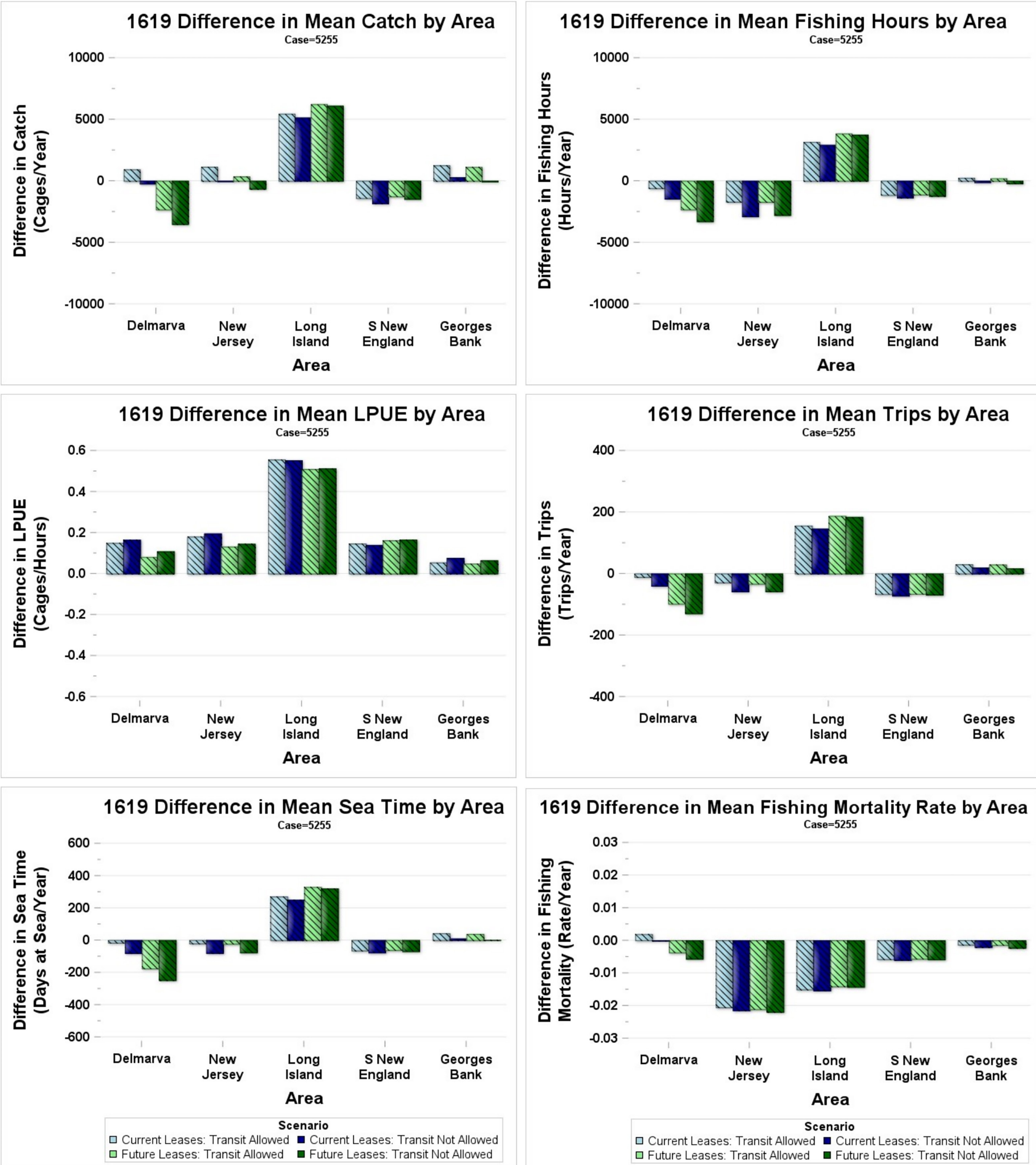

FIGURE 10 | Future wind case 5255 compared to 1619 no wind case: the mean of each fishery metric and transit scenario are calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario in 1619 (Mean Wind-1619 Mean No Wind) for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE:cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

however, release an extensive economic analysis of the potential impacts of OWF on the fisheries of the Northwestern Atlantic. The Atlantic surfclam fishery was identified as one of the fisheries of concern. A subsequent economic evaluation identified substantive economic concerns for this fishery, particularly for surfclams landed in ports in New Jersey and northern Maryland (Scheld et al. 2022).

Wind turbine arrays that will be installed in several OWF projects along the US East Coast (BOEM 2024a) are static occupiers of the continental shelf, unmoved by the influence of warming ocean temperatures over the decades of their anticipated performance lifespan. According to the Office of Energy Efficiency and Renewable Energy, resulting from a survey of US wind industry professionals in 2019, the lifespan of each turbine is approximately 30 years (U.S. Department of Energy 2023). Replacements and repairs of the foundation, towers, and individual turbine components will be ongoing after initial installation and inevitably disturbing to surrounding species and fisheries. Though sedentary bivalves are not

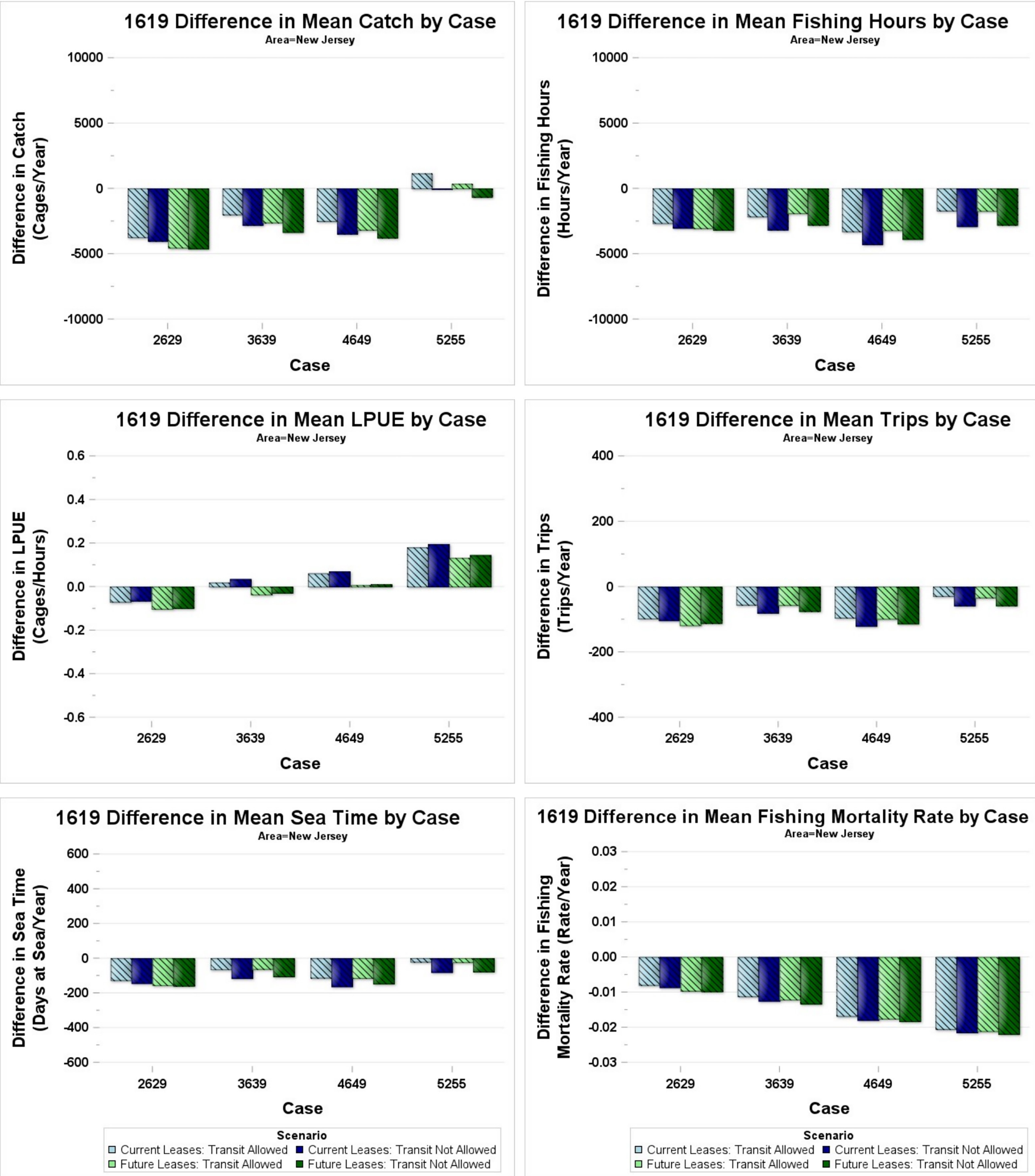

FIGURE 11 | New Jersey area compared to 1619 no wind case: the mean of each fishery metric and transit scenario are calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario in 1619 (Mean Wind-1619 Mean No Wind) for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE: cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

nearly as mobile as the demersal and pelagic fish communities carrying out noteworthy and rapid redistributions under the influence of warming temperatures (Rose 2005; Rijnsdorp et al. 2009; Lucey and Nye 2010; Langan et al. 2021), sedentary species such as the Atlantic surfclam and other bivalves have demonstrated a substantial capacity to shift their geographic footprint within decadal or even half-decadal time periods (Thomas et al. 2016; Hofmann et al. 2018; Weinert et al. 2021). This is even more remarkable in the MAB considering that the primary dispersal mechanism is waterborne larvae transported from their place of birth and the necessary movement of the species' range consequent of rising temperatures through larval transport against the direction of net water transport to the west and south throughout most of the MAB (Zhang et al. 2015; Neto, Langan, and Palter 2021).

Projections of future range occupations have become part of the research portfolio directed at climate change (Coro et al. 2016; Lotze et al. 2019; McHenry et al. 2019; Weinert et al. 2021), but to date, such projections have neither considered the integration

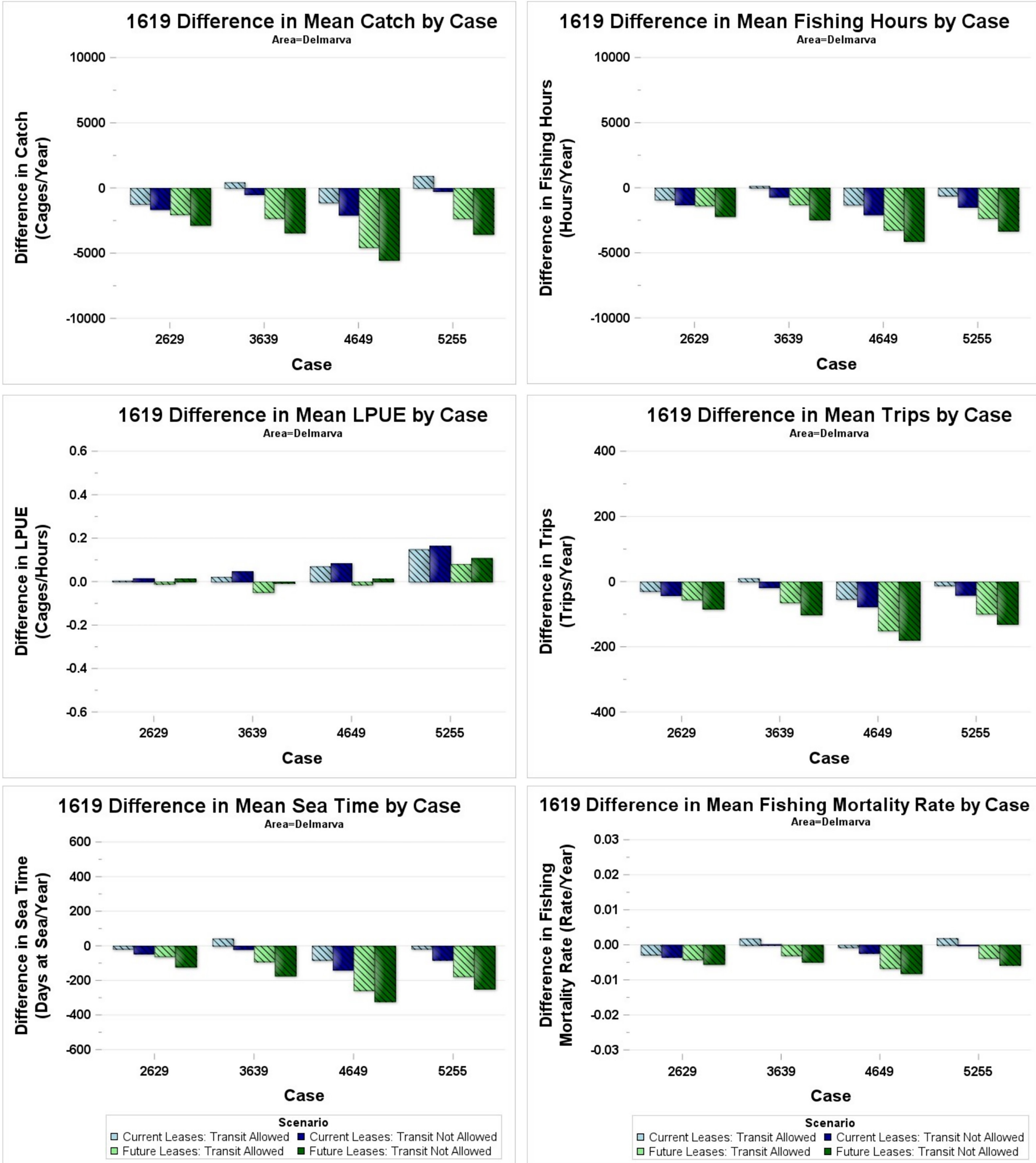

FIGURE 12 | Delmarva area compared to 1619 no wind case: the mean of each fishery metric and transit scenario are calculated as the difference between the mean OWF scenario minus the mean no-wind-farm scenario in 1619 (Mean Wind-1619 Mean No Wind) for each of the regions identified in Figure 1. Fishing metrics include catch (cages per year), hours fishing per year, landings per unit effort (LPUE: cages per hour), yearly trips, yearly days at sea, and fishing mortality rate (yr^{-1}). Scenario legend applies for all metrics.

of species' shifting range with fisheries response ambits nor the influence of both interacting with competitive uses of the continental shelf, most of which are agnostic to climate change. This study marries two critical questions concerning the future of exploitation of the continental shelf during a period of rapid climate change: the fishery as it reacts to the redistribution of the target species and the interaction with unmoving, but constraining, influences on the performance of the fishing endeavor; particularly in this case, the interaction of wind energy development, the Atlantic surfclam fishery, and the influence of climate change.

4.2 | Influence of Changing Stock Size With Climate Change

To appreciate the influence of offshore wind during a period of climate change on the fishery, it is first important to understand the direct influence of climate change on the geographic range and carrying capacity of the Atlantic surfclam and on the surfclam fishery detailed in Spencer et al. (Early View). The Atlantic surfclam fishery is faced with an uncertain future in the face of rising water temperatures, northern and offshore range shifts, overlaps with other species such as the ocean quahog, notwithstanding the overlap with OWF development (Powell, Kuykendall, and Moreno 2017; Powell et al. 2021; Munroe et al. 2022; Scheld et al. 2022; Methratta et al. 2023; Stromp, Scheld et al. 2023). Increasing bottom water temperatures in the MAB are predicted to increase the Atlantic surfclam stock as a response to an expanding geographic footprint occupied by conducive water temperatures. Though at first seemingly counterintuitive, given the sensitivity of the species to heatwaves inshore (Kim and Powell 2004; Weinberg et al. 2005; Narváez et al. 2015), the response pattern is an anticipated outgrowth of the erosion of the Cold Pool as the waters of the Northwestern Atlantic warm (Chen and Curchitser 2020; Friedland et al. 2022). The Cold Pool presently occupies a substantial portion of the middle to outer continental shelf from Georges Bank to southern Delmarva (Bignami and Hopkins 2003; Lentz 2017; Chen and Curchitser 2020; Friedland et al. 2020), permitting the persistence of boreal species, originally occupying a large portion of the continental shelf in this region during the Little Ice Age (LeClaire et al. 2022, 2023), at latitudes well south of the typically accepted boreal-temperate zone boundary (Engle and Summers 1999; Hale 2010).

Simulations of the anticipated fishery performance during the 1619–5255 period are highlighted in Spencer et al. (Early View) and show the anticipated response to the increase in available surfclam biomass in the form of rising LPUE, increased catch, and declining fishing mortality rate under the restriction, as also imposed here, that the fishing capacity in the fishery does not increase with the addition of vessels capable of carrying a larger number of cages per trip and that present homeports remain as primary homeports into the future. The trends in stock biomass and the response by the fishery exert a primary influence on the outcome of simulations considering the interaction of the fishery with OWF.

4.3 | Influence of OWF Development With Climate Change

The forecasted increase in Atlantic surfclam biomass may offset the predicted decrease in fishery metrics due to OWF development identified by Scheld et al. (2022) as well as the constraint imposed by the expanding surfclam–ocean quahog range overlap. The potential influence of OWF on the marine ecosystem encompasses a range of issues including underwater sound (Sigray et al. 2022), development of a hard-bottom fauna in a region typically without such substrata (Hoffmann et al. 2000; Bray, Kassis, and Hall-Spencer 2017; Coolen et al. 2020b), modification of thermal stratification (Miles et al. 2021; Horwitz et al. 2022), and changes in current velocity (Commito et al. 2019). Fisheries interactions are highly variable depending on gear used and mobility of the species, but for the Atlantic surfclam, the primary issues are few, distinctive, and unrelenting. The fishery uses large hydraulic dredges that limit deployment in restricted locations and in locations with bottom obstructions (Parker 1971; Meyer, Cooper, and Pecci 1981). Fishing within an array of wind turbines distributed on an approximately 1-nautical mile grid is likely to be infeasible. Whether steaming through wind farms remains feasible is unknown; however, vessels can be maneuvered successfully under space-limited constraints (Poussard, Powell, and Hennen 2021), but only during good weather. Thus, fishing grounds are restricted by OWF development, and transit around, rather than through, the wind farms is likely to be required under a selected range of sea states. Not surprisingly, regardless of the time period, the most serious effects are recorded for the no-transit cases.

The surfclam fishery is a high-volume, low-value fishery. Thus, the viability of the industry depends upon high catches over short time spans. The surfclams also cannot be kept on board for more than about 1.5 days without spoilage. Steaming around wind turbine arrays adds time at sea, so fishing in offshore locations with high catches may be restricted to cold-temperature months. Consequently, an expectation is that OWF might lower LPUE, increase time at sea, and reduce trip number during high-temperature months, all of which would reduce catch. For these reasons, an anticipated outcome is the tendency for cases in which transit is disallowed and in which a full buildout of OWF is envisioned are likely to be the most noticeably impactful on the fishery.

Five time periods were simulated during which, initially, the surfclam biomass decreased (2629) but then increased to 5255 because of warming temperatures. During this time, the surfclam stock is expected to expand its domain over the continental shelf, offshore, while yielding some, but a more limited area of occupation inshore. Thus, potential fishing grounds increase, as does stock biomass, leading, all else being equal, to higher LPUE, higher catches, and reduced time at sea. The influence of OWF on the stock is dramatic and consistent (Figure 2). Catch declines, the number of trips declines, and time at sea declines consistent with the decline in trips taken. Interestingly, LPUE tends to increase, though very modestly, consistent with a reduction in time spent fishing. The origin of this, at first unexpected, outcome is the necessity of captains to steam further offshore or up or down-coast to available fishing grounds, requiring targeting of grounds yielding the highest LPUE to compensate for the increased distance traveled. But the overwhelming impact on catch, which declines substantially, is produced by a decrease in the number of trips taken as certain vessels at certain times of the year cannot fulfill requirements imposed by a trip time restriction of 36–40 h between the time that fishing begins and the time when the vessel returns to the dock. This outcome does not change over time because the location of OWF development exerts a permanent impediment to transit from available ports to fishing grounds. Not surprisingly, that penalty is increased by the no-transit assumption and further increased by the expansion of OWF to include planned future OWF buildout.

The impact of OWF varies considerably among regions and is consistently highest off New Jersey and then off Delmarva. A large fraction of the Atlantic surfclam fishery lands clams in Atlantic City, New Jersey, with some catch being landed in Point Pleasant, NJ, and Ocean City, MD. Plans for OWF development include substantial leases with locations that impede transit into and out of these ports and which occupy historically important fishing grounds (e.g., NEFSC 2017). Consequently, catch declines, LPUE declines in the New Jersey region, time at sea declines, and the number of trips declines substantially in 2629. The outcome is relatively similar in 5255, despite the higher overall biomass of surfclams because the stock has moved primarily offshore, whereas relief of the OWF impediment would best be obtained if the stock had moved alongshore. Results are qualitatively similar in the Delmarva region.

Across time, for the New Jersey region, the only noteworthy change is a tendency for LPUE to increase as biomass increases, thereby limiting the OWF impact, but this change is insufficient to substantially change the outcome. The trend in the Delmarva region is more chaotic, primarily because simulated captains chose to transit inshore or offshore of the wind farms south of Atlantic City, consistent with the decline in biomass inshore with warming temperatures and increasing biomass offshore. As this range shift matures, the OWF impact increases, as vessels must now transit offshore of the wind farms to fishing grounds (Figure 4). Unsurprisingly, the impact of the no-transit assumption is distinctly larger in this region than elsewhere and overwhelms all other trends.

4.4 | Influence of OWF Development With Climate Change: The 1619 Comparison

Over the entire stock, the differences between the 1619 no-OWF case and the future OWF cases are primarily a function of expanding surfclam biomass and the fishery response. Most metrics increase off Long Island consistent with the substantive expansion of surfclam biomass in that region. Lesser increases or decreases occur in Delmarva and on Georges Bank consistent with the more limited change in biomass in these two regions (Spencer et al. Early View). LPUE generally increases enough to overcome negative OWF impacts so that catch remains similar for all regions outside of Long Island.

A closer look at New Jersey reveals the strong trend towards minimizing OWF impact over time, with catch returning by 5255 to 1619 levels, expanding LPUE, declining time at sea, and plummeting fishing mortality rate. The number of trips taken is more resistant, as the impact of vessel capability relative to time at sea limitations remains, but this impact also declines by 5255. The same trends remain off Delmarva, although the distinctive impact of no transit remains as vessels must steam around OWF from northern ports. Besides the logistical impediment that remains, the impediment of OWF is not ameliorated by increasing biomass in this region as in New Jersey because biomass does not respond nearly as positively to warming temperatures in Delmarva. Surfclams move offshore, but unlike more northern regions, loss inshore is more balanced with gains offshore.

4.5 | Caveats

The present-day lease scenarios within the SEFES model were sourced from BOEM active leases and planning efforts (BOEM 2024a). The planned future scenarios are based on BOEM call areas or areas that could be leased in the future. The sizes of these latter areas are approximate and may be larger or smaller than realized future leased areas. Minor changes to leased areas in the MAB after BOEM (2024a) are not included in the present analysis, and lease holdings remain fluid, so the present analysis represents an evaluation of a single discrete OWF development plan. Industry adaptations are also not built into the SEFES model (e.g., port switching and increased use of refrigeration).

A question arises as to the fairness of comparing conditions with and without OWF within future years. Such comparisons have been made herein by comparing fishery performance at any future time with and without OWF buildout. This is inherently instructive as it emphasizes what otherwise would have been the performance of the fishery at that time, had the BOEM (2024b) OWF plan not been implemented. On the other hand, if buildout is successful, the fishery will never observe a future case without wind farms. Thus, their comparison can only be between the present-day case without OWF and the future case, including OWF buildout. That comparison is dramatically different in many ways from the comparison between the OWF and no OWF cases within the same time frame. For this reason, this second evaluation of the results using a comparison with the no-OWF case for 1619 is provided. The differential in results between the two methods emphasizes the need to consider both options in any evaluation of OWF impact.

5 | Conclusion

A sustainable future must support the coexistence between fisheries and clean energy. The coastal ocean uses are continuing to expand with time, creating larger competitive pressures between established fisheries and new clean energy developments (Munroe et al. 2022). The MAB has many sites approved for the installation of large-scale wind turbine farms with locations of these projects ranging from offshore Rhode Island to offshore Delmarva. These initially approved projects and those that will follow have the potential to disrupt established fishing grounds that are already experiencing restrictions from temperature-driven range shifts and species mixing (Stromp, Scheld et al. 2023).

A complicated contrast is presented as efforts to mitigate climate change grow by lessening the nation's dependence on fossil fuels by moving renewable energy offshore while potentially overlapping with fisheries that depend on species that are moving north due to ocean warming trends (Spencer et al. Early View). The simulations reported here, and in preceding similar studies (Munroe et al. 2022; Scheld et al. 2022; Stromp, Scheld et al. 2023), investigate how restricting transit and fishing in planned lease areas in the northeast continental shelf could disrupt fishing activity in the future decades compared to scenarios when no wind farms are present. Simulations suggest that, as the capacity of OWF continues to increase, so will the competition for space and resources that are economically and commercially important to surrounding fishing communities. Successful and sustainable coexistence between the offshore wind energy industry and the Atlantic surfclam fishery is achievable if considerations are made for developing new multi-use practices centered around fisheries as OWF development continues to expand.

The simulations presented emphasize the importance of addressing the evaluation of OWF impact within the context of climate change. Particularly for sedentary species, the distribution of the core of the range as it shifts relative to OWF installations is key. A critical finding is the degree to which the interpretation of impact is determined by the method of comparison. Atlantic surfclams are not unique in their positive response to warming temperatures over the coming half-century, but they do represent a particularly potent example of a positive outcome to climate change, and that response poses an interesting conundrum as to the evaluation of OWF impact. Within a given time period, OWF consistently impacts the surfclam fishery negatively, as the primary impediment generated by the interference of vessel transit and occupation of productive fishing grounds does not change materially. On the other hand, biomass expansion is dramatically ameliorative of this impact so that a comparison of future OWF impacts to initial conditions (1619 as defined herein) shows a steadily decreasing impact on the fishery over time. How the two options for defining the impact of OWF on the Atlantic surfclam fishery are to be weighed is a compelling quandary facing all parties in this competition for use of the continental shelf.

Author Contributions

A.L.M. ran simulations, produced figures, and drafted manuscript. E.N.P. and A.M.S. provided sections of the manuscript. A.L.M., E.N.P., E.E.H., J.M.K., D.M.M., S.B., A.M.S., and M.M.S. contributed to the development of the SEFES model as implemented in this study. E.C. provided bottom temperature data from the hydrodynamics model projections. All authors provided comments and suggestions on revisions.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The source data for the Atlantic surfclam survey data can be accessed online at NOAA Fisheries: Northeast Fisheries Science Center page. Information on the size and distribution of offshore wind farms can be obtained from the Bureau of Ocean Energy Management. Projected bottom water temperatures used for model input are available by contacting the authors. Detailed results of simulations are provided in the Supporting Information.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.