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THE INFLUENCE OF RANGE SHIFTS AND WIND ENERGY ON THE ATLANTIC SURFCLAM (SPISULA SOLIDISSIMA) AND OCEAN QUAHOG (ARCTICA ISLANDICA) FISHERIES ON THE U.S. OUTER CONTINENTAL SHELF

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by

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ABSTRACT

The Atlantic surfclam, *Spisula solidissima*, is a biomass dominant bivalve of the Northwestern Atlantic. The surfclam's historic range extended from Cape Hatteras to Georges Bank, but recent decades of warming bottom water temperatures have caused the surfclam to shift its range to cooler waters north and offshore within the range of the ocean quahog, *Arctica islandica*. An ecotone now exists over much of the offshore range of the surfclam in which surfclams and ocean quahogs co-occur. Regulations prohibit fishers from landing both species in the same catch, limiting fishing to locations where the target species can be sorted on deck. Wind energy development on the US outer continental shelf will further restrict available fishing grounds. SEFES, a spatially-explicit model of the Atlantic surfclam fishery was used to run simulations of species overlap in conjunction with wind farm development scenarios to evaluate the consequences of fishery displacement. Model scenarios with less restrictive fishing penalties to allow on-board sorting of clams exhibited higher raw catch numbers but also greater reductions in revenue and increased cost after wind farm implementation. A 2021 at-sea survey sampling of the overlap region was also conducted with the purpose of mapping fishable concentrations of surfclams and ocean quahogs. Species overlap between surfclams and ocean quahogs is most prominent in the 40-55-m depth range where size and density of surfclams declines with decreasing temperature, indicative of newly recruited populations in offshore, cooler waters. This analysis emphasizes the potential for economic disruption of fisheries and highlights the need for regulatory changes to allow mixed catches and landings.

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DEDICATION

This thesis is dedicated to my wife Maddi, for (gently) pushing me to apply to graduate school and supporting me with love and pride during the last two years, and to our feline children Willow, Finn, and Magnolia for being the best and cutest work-from-home companions.

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LIST OF ABBREVIATIONS

USM	The University of Southern Mississippi
SCEMFIS	Science Center for Marine Fisheries
NSF	National Science Foundation
NMFS	National Marine Fisheries Service
MAB	Mid-Atlantic Bight
NEFSC	Northeast Fisheries Science Center
ITQ	Individual transferrable quota
BOEM	Bureau of Ocean Energy Management
SEFES	Spatially-explicit Fishery Economics Simulator
TMS	Ten-minute square
CPUE	Catch per unit effort
LPUE	Landings per unit effort
GARFO	Greater Atlantic Regional Fisheries Office
BIWF	Block Island Wind Farm
AMOC	Atlantic Meridional Overturning Circulation
NAO	North Atlantic Oscillation
ROMS	Regional Ocean Modeling System
MAFMC	Mid-Atlantic Fishery Management Council

CHAPTER I INTRODUCTION

1.1 Background

The Atlantic surfclam (*Spisula solidissima*) is a cool-temperate species and a benthic biomass dominant on the northeast continental shelf of the U.S. Historically, this clam ranged from Cape Hatteras to Georges Bank with an extension into the extreme inshore of the Gulf of Maine (Merrill and Ropes 1969, Palmer 1991, Hofmann et al. 2018). Its fishery produces over US$30 million in annual revenue and, in conjunction with the ocean quahog (*Arctica islandica*) fishery, produces over US$1.3 billion in total economic impact (Murray 2016). The Atlantic surfclam fishery occurs in the waters of the Mid-Atlantic Bight (MAB) and on Georges Bank (NEFSC 2020) which, in response to climate change, have experienced warming rates three times faster than the global average (Pershing et al., 2015, Saba et al., 2016). Atlantic surfclams are particularly sensitive to elevated bottom water temperatures above 21°C and generally do not survive above 25°C (Munroe et al. 2013, Powell et al. 2017, but see increased temperature tolerance for juveniles, Aquafredda et al. 2019). The upper thermal optimum at about 21°C is determined in large measure by the response of filtration rate to temperature (Munroe et al. 2013). Above this temperature, surfclams experience rapid physiological decline as their respiration rate increases faster than ingestion rate. Scope for growth declines and leads to starvation, ultimately resulting in mortality if exposed to higher temperatures for extended periods of time (Kim and Powell 2004, Weinberg et al. 2005, Narváez et al. 2015).

As a result of warming bottom water temperatures, the Atlantic surfclam has shifted its range offshore into deeper water (Hennen et al. 2018, Hofmann et al. 2018, Powell et al. 2020a). A northward and offshore transgression of the inshore southern range boundary likely began in the 1970s (Hofmann et al. 2018). A subsequent movement of surfclams offshore has been recorded as far north as Georges Bank (Timbs et al. 2019). Kim and Powell (2004) documented a surfclam mass-mortality event inshore off the Delmarva Peninsula circa 2000, pushing the species' southern boundary further northward and offshore (Weinberg et al. 2005). In the waters off Long Island, declines in Atlantic surfclam biomass inshore (Hornstein et al. 2018) and resulting offshore biomass increases (NEFSC 2017) give added support to a cross-shelf range expansion, also well documented off New Jersey by Weinberg et al. (2005) and Hofmann et al. (2018). East of Nantucket, a greater abundance of smaller surfclams in addition to few large animals found at offshore sites is consistent with recruitment of Atlantic surfclams into deeper water circa 2004 (Powell et al. 2019, Powell et al. 2020a). As a consequence, the Atlantic surfclam fishery, originally concentrated in the 1970s and 1980s in the southern portion of the Mid-Atlantic Bight (Loesch and Ropes 1977, Ropes 1982), has shifted northward and offshore with the changing range of the stock through the subsequent decades (McCay et al. 2011, NEFSC 2020).

Another biomass-dominant clam species of the North Atlantic is the ocean quahog (*Arctica islandica*). The ocean quahog is a boreal clam with a range extension into the Mid-Atlantic Bight courtesy of the Cold Pool, a body of cold water trapped during the summer by thermal stratification (Miles et al. 2021), that permits a range extension into lower latitudes than defined by the nearshore boreal-temperate provincial boundary (Engle and Summers 1999, Hale 2010). Ocean quahogs are most abundant at 30-60m depth in this region (Dahlgren et al. 2000) and have historically resided in waters offshore of those occupied by the Atlantic surfclam with relatively little overlap along the inshore range boundary presumably due to the stability of the temperature gradient maintained by the Cold Pool. However, the historically narrow ecotone between ocean quahogs and Atlantic surfclams has expanded dramatically in recent years due to the Atlantic surfclam's rapid range expansion offshore relative to the more stable inshore boundary of the ocean quahog (Powell et al. 2020b). The limited response to rising temperatures by the ocean quahog is thought in part to originate from the ability of this clam to burrow deeply and estivate for extended periods, thereby escaping extreme fall bottom water temperatures. Consequently, live Atlantic surfclams are now found within the inshore range of ocean quahogs (Powell et al. 2017, 2020b) and the footprint of this overlap now stretches over an extensive depth zone throughout much of the Mid-Atlantic Bight.

Presently, commercial fishing vessels in the MAB are not allowed to land Atlantic surfclams and ocean quahogs in the same catch, a consequence that facilitates tracking landings and limits illegal harvesting. This constraint limits fishing locations to where both species can be sorted on deck efficiently with limited deck crew. Current industry guidance puts the amount of mixing deemed sortable on board at one individual of one species in every 25 total clams. The historically limited species overlap present throughout much of the history of the fishery produced a *de minimis* economic impact from the consequently limited areal restriction to the fishery while generating a fishery with a renowned low level of bycatch discards. This latter exemplary record has degraded dramatically in recent years as the continual range shift of Atlantic surfclams offshore jeopardizes both the fishery's profitability by restricting access to a shrinking region of the Atlantic surfclam stock and the fishery's exemplary record of minimal discarding.

In addition to warming water temperatures constraining access of the fishery to the stock due to overlap with ocean quahogs, the Atlantic surfclam fishery is also vulnerable to wind energy development. Over 1.7 million acres of the United States outer continental shelf has been leased for renewable energy projects (BOEM 2021) with the majority of leases designated for the erection of arrays of wind turbine monopoles. A lease or leased area is defined as a region permitted for wind energy development with a 1-NM spacing between monopoles assumed. The distribution of the Atlantic surfclam overlaps considerably with the current and planned wind farm leases (Munroe et al. 2022). Ecological and commercial fisheries' implications of offshore wind development include habitat loss, modified larval dispersal, fishing exclusion, and fishing effort displacement (Heery et al. 2017, Gill et al. 2020, Methratta et al. 2020, Negro et al. 2020). Conflicts between fishing and energy sectors arise as users compete for space and resources (Bidwell 2017, Haggett et al. 2020), and this is particularly true for fisheries dependent on sedentary marine species. The Atlantic surfclam fishery operates large vessels with hydraulic dredges (Parker 1971), making navigation and harvest challenging (Kirkpatrick et al. 2017), particularly within potential navigational and fishing corridors of 1 NM or less. Economic sustainability of the Atlantic surfclam fishery hinges on the ability to fish outside of leased areas. As little of the leased area includes depths where Atlantic surfclams and ocean quahogs now overlap, loss of fishing grounds is likely to include productive locations both inshore and offshore, with few routes of amelioration save a modification to the present restriction to single-species landings.

1.2 Project Objectives

This thesis examines the Atlantic surfclam's shift in range in conjunction with ongoing wind energy development along the eastern continental shelf of the United States. The Spatially-explicit fishery economics simulator (SEFES) an existing agent-based model where agents are individual vessels in the Atlantic surfclam fleet, (Kuykendall et al. 2017, Kuykendall et al. 2019, Powell et al. 2015, Powell et al. 2016) was used to run five rounds of simulations, varying the degree of these fishing constraints imposed by the across-shelf distribution of surfclams and ocean quahogs. In each of the five rounds, five different wind energy development scenarios for both current and future leases were tested. Fishing activity and economics metrics were evaluated for twenty-five total simulations using *R*, a statistical computing and graphics software, and with methods outlined in Scheld et al. (2022). Results were then compared across simulations and utilized as a tool for predicting implications of range shifts and wind energy development on the surfclam fishery.

A second, but similar, objective involves examining the developing ecotone between Atlantic surfclams and ocean quahogs (Powell et al. 2020b). This ecotone is geographically extensive and is produced by climate change. A recent research cruise in September 2021 identified further areas of overlap between the two species, extending the known range of the ecotone. Abundance and size frequency data from this cruise for surfclams and ocean quahogs were analyzed along with temperatures from the Doppio model, a ROMS (Regional Ocean Modeling System) based model of the Mid-Atlantic Bight (Lopez et al. 2020). Information from Doppio, in addition to cruise data, was used to interpret cross-shelf trends in size frequency and abundance. Results of the ecotone analysis map surfclam expansion, as evidenced by juveniles and small size class individuals offshore. These chapters combined led to a more thorough description of the ecotone between Atlantic surfclams and ocean quahogs and its dynamics, which remain unstudied.

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CHAPTER II – INTERACTIVE EFFECTS OF CLIMATE CHANGE-INDUCED RANGE SHIFTS AND WIND ENERGY DEVELOPMENT ON FUTURE ECONOMIC CONDITIONS OF THE ATLANTIC SURFCLAM FISHERY

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2.1 Introduction

The Atlantic surfclam (*Spisula solidissima*), a cool-temperate species, is a benthic biomass dominant on the northeast U.S. continental shelf. The historical range of the Atlantic surfclam was from Cape Hatteras to Georges Bank, and along the extreme inshore of the Gulf of Maine (Merrill and Ropes 1969, Palmer 1991, Hofmann et al. 2018). The Atlantic surfclam fishery produces over US$30 million in annual revenue (ex-vessel) and, combined with the ocean quahog (*Arctica islandica*) fishery (US$53.6 million in annual revenue, ex-vessel), produces over US$1.3 billion in total economic impact (Murray 2016). The Atlantic surfclam fishery operates in the Mid-Atlantic Bight (MAB) and on Georges Bank (NEFSC 2020) where climate-induced warming rates are much faster than the global average (Pershing et al. 2015, Saba et al. 2016). Atlantic surfclams are particularly sensitive to elevated bottom water temperatures above 21°C and generally do not survive above 25°C (Munroe et al. 2013, Powell et al. 2017); however, juveniles can exhibit increased temperature tolerance (Acquafredda et al. 2018). The upper thermal optimum at about 21°C is determined primarily by temperature effects on filtration rate (Munroe et al. 2013). Above this temperature, Atlantic surfclams experience rapid physiological decline, principally through reduced feeding leading to starvation, ultimately resulting in mortality when exposed to warm temperatures for an extended period of time (Kim and Powell 2004, Weinberg et al. 2005, Narváez et al. 2015).

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

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

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

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

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

2.2 Methods

2.2.1 SEFES model

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

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

2.2.2 Atlantic surfclam and ocean quahog range overlap

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

The TMSs where ocean quahogs are found were used to construct a mask for the simulations that consider fishing in overlap regions. A mask defines a set of TMS of a specific type; in this paper, the ocean quahog mask defines TMS where 4% or more of the catch are ocean quahogs either by direct observation or captains' reports. Figure 2 shows the original mask obtained from stock surveys and captain reports and used by Munroe et al. (2022) and Scheld et al. (2022). A portion of the ocean quahog mask, the region south of Hudson Canyon, was surveyed separately in September of 2021. Figure 3 shows overlap regions with a gradient of percent ocean quahog catch amongst sampled stations. Any locations in the survey with mixed catch of Atlantic surfclams and ocean quahogs were applied to the existing ocean quahog mask to produce a newer, updated mask. The updated mask is used in present simulations. In masked TMSs, a catch penalty is invoked for vessels fishing in an overlap area. The ocean quahog catch penalty is subtracted from the overall skill level of the captain. For example, the captains' skill level is set at a 60% catch efficiency (catch efficiency recorded as the fraction of the hour fishing in which the dredge is on the bottom catching clams) in unmasked TMSs and a 50% ocean quahog penalty imposed in masked TMSs reduces the overall skill to 10% (0.60 – 0.50 = 0.10). This reduced skill level was estimated based on reports from the fishery that indicated an unwillingness or inability to sort catch on deck when the fraction of the catch included >4% ocean quahog.

2.2.3 Model implementation

Five sets of simulations were used to assess the effect of changing skill level on fishing activity. In these simulations the penalties imposed on skill level ranged from no penalty (Q0, Table 1) to 60% penalty (Q6, Table 1), with intermediate cases of 30%, 40% and 50% penalties, Q3, Q4, and Q5 (Table 1), respectively. The simulations with a 50% penalty, Q5, represent a “business-as-usual” scenario consistent with standard present-day fleet behavior (Munroe et al. 2022) with the captain’s skill reduced to 10% in regions of ocean quahog overlap as described earlier. These simulations, representing present-day conditions, were verified against observed fishery performance by Munroe et al. (2022). Removal of the ocean quahog mask, simulation scenario Q0, allows captains to fish in any masked TMS without an imposed ocean quahog catch penalty and thus permits an estimate of the economic cost of species overlap. For both the Q3 and Q4 scenarios, the ocean quahog penalty is reduced relative to the business-as-usual simulation scenario. The economics of the Atlantic surfclam fishery depend upon a highly mechanized fishing procedure that limits total vessel crew. A consequence of limited crew is limited sorting capacity on-deck. The lower penalties describe cases of improved sorting capability within the same time-at-sea constraints. Q3 imposes a penalty of 30% (0.60 - 0.30 = 0.30 or 30% efficiency) and Q4 imposes a penalty of 0.40 (0.60 - 0.40 = 0.20 or 20% efficiency). Q3 and Q4 scenarios were chosen to represent the potential economic investment needed to sort surfclams and ocean quahogs on-deck, whether this investment be in man-power – adding an extra crew member – or in sorting technology (Bhargava and Bansal 2021). Investments assume that some flexibility exists in the degree of economic investment necessary to permit fishing in regions of species overlap. Q3 and

Q4, as opposed to Q0, are assumed to be potentially economically viable options balancing the cost of sorting relative to the economic gain of increased catch. A 10% or 20% penalty was not examined as the increased on-deck sorting would require much more time or crew allocated to sorting the two species than is currently feasible while maintaining an economically viable CPUE. The final simulation scenario, Q6, raises the quahog penalty to 0.60, equal to the captain skill, so that, in marked TMSs, the catch efficiency is zero (0.60 – 0.60 = 0.00) and no Atlantic surfclams can be caught.

For each of the five simulation sets, five possible wind farm displacement conditions are considered, resulting in a total of 25 simulation scenarios (Table 2). Scenarios include no wind farm constraints on fishing or transit (00, Table 2), current wind farm leases with transit allowed but no fishing (1T, Table 2), and without transit or fishing allowed (1N, Table 2), and current and future proposed lease wind farm lease sites with transit allowed but no fishing (2T, Table 2) and without fishing or transit allowed (2N, Table 2). At this time, very limited construction of monopoles has occurred within purchased leases. Fishing vessels are currently able to fish and transit within the leases as they have always been able to do. Simulations of the effect of wind farms on the fishery assume that the leases are fully built out with monopoles sited on a 1-NM grid. Restrictions on transit and fishing within leases will likely not be prohibited through federal legislation, but rather through vessel insurance policies and owner or captain preference. Only no-fishing scenarios are simulated for wind farm cases as it is unrealistic for vessels to be able to fish within developed leases because of undersea power cables and vessel maneuverability. In Europe, where offshore wind farms are currently in operation, use of mobile gear within leases is generally restricted (Gill et al.

2020). An Atlantic surfclam vessel fishing between turbines would need to avoid monopole support structures, rock reinforcements, and buried power cables resulting in a lower level of efficiency compared to an unleased area (Scheld et al. 2022). Whether transit will occur is unclear and, hence, simulations address both the no transit and transit allowed options.

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

2.2.4 Fishing activity analyses

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

2.2.5 Economic analyses

Economic impacts are based on fleet revenue, total fleet cost, average cost per cage landed (standard industry conversion: 1 cage = 32 bushels; 1 clam bushel = 53.2 liters), and average fuel cost per cage landed (all US$). Atlantic surfclam fishing fleet economics are derived from SEFES model output in collaboration with industry members, captains, and seafood companies that purchase and process Atlantic surfclams (Scheld et al. 2022). Economic parameters have been previously assessed in Scheld et al. (2022) using Atlantic surfclam vessel trip reports from 2015-2019 obtained from NOAA Fisheries' Greater Atlantic Regional Fisheries Office (GARFO, 2021). The price per cage landed is set to US$458.75 and is based on an average of annual bushel prices from 2017-2019 (NEFSC 2020). Fuel prices by port are annual average prices for the New England and Central Atlantic regions, adjusted for inflation (EIA 2020). Detailed calculations for Atlantic surfclam fishing fleet revenues and costs can be found in Scheld et al. (equations 1-7, 2022).

2.3 Results

2.3.1 Ocean quahog overlap comparisons – fishing activity metrics

Changes in fishing activity metrics vary across simulations with different ocean quahog penalties (Figure 4, Table A.1, Table A.3). All percentage values represent the range of fishing activity metrics across all five windfarm cases for one ocean quahog penalty simulation. LPUE predictably declined in each simulation with an ocean quahog mask restriction compared to those with no mask, with LPUE declining as the ocean quahog penalty increased. LPUE in cases with a 30% penalty was reduced by 10.24-13.84%, whereas LPUE in cases with 40% and 50% penalties decreased by 11.63-16.66% and 12.38-18.41%, respectively. Substantial declines in LPUE for Q6 (54.39-59.77%) are likely a result of the extreme limitation in the number of fishable TMSs.

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

2.3.2 Ocean quahog overlap comparisons – economic metrics

Cases with greater ocean quahog penalties produced larger reductions in revenue (Figure 5, Table A.2, Table A.4). All percentage values represent the range of economic metrics across all five windfarm cases for one ocean quahog penalty simulation. Business-as-usual cases (Q5) declined in revenue up to 28.56% compared to cases with no ocean quahog restrictions (Q000). Lowering the ocean quahog penalty to 40% (Q4) or 30% (Q3) reduced losses in revenue, but revenue still declined, by 22.58-26.23%. Revenue dropped sharply with the 100% ocean quahog penalty (Q6), by up to 62.36%.

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

2.3.3 Wind farm comparisons – fishing activity metrics

All percentage values represent the range of fishing activity metrics across all five ocean quahog penalty cases for one wind farm designation. Compared to the business-as-usual scenario, the scenario presumed to be the ocean quahog penalty representative of present-day conditions (Q5), average LPUE increased in most cases with wind farm development (Figure 6, Table A.1, Table A.5). Exceptions include cases Q02T and Q02N, where LPUE decreased approximately 3-4% from Q000. A reduction in available TMSs to fish in due to wind farms results in boats targeting locations where Atlantic surfclam density is high, thus increasing LPUE, but at the expense of increased time at sea.

For each wind farm case across all ocean quahog penalties, average time at sea rose considerably when transit through wind farms was not allowed (1N, 2N). The greatest time spent at sea occurred in the no transit cases which imposed the greatest wind farm footprints (Q61N, Q62N) where the percent increase in time at sea was 23.00% and 31.24%, respectively.

In most simulations where no transit through wind farms was allowed, time fishing decreased as boats were required to spend additional time traveling to and from fishing grounds. In comparison, average time fishing improved in simulations that allowed transit through wind farms, becoming relatively similar to the case without wind farms (00). A glaring exception is found in Q62T and Q62N, where between 9.64-13.78% less time was dedicated to fishing compared to the business-as-usual scenario.

Total trips decreased in every simulation with wind farm development. Scenarios with only current leases (1N,1T) exhibited between 1.56-13.42% fewer trips, whereas those with current and future wind farms (2N, 2T) produced a much greater reduction in the number of trips, 2.91-18.99%. These trends, like the others, come as a consequence of reductions in fishable area and the time needed to transit around wind farms. In Q6, such few fishable TMSs exist that restricting transit (Q61N, Q62N) causes larger percent changes (13.42%, 18.99%) compared to the other four cases (Figure 6).

In all scenarios in which time at sea increases, LPUE tends to increase. The inference is that captains attempt to ameliorate the penalty imposed by an increase in the required time steaming farther from port by targeting TMSs farther from port that nonetheless have higher Atlantic surfclam densities. For example, in case Q42N, LPUE increased by 2.27% compensating in part for a 10.56% increase in time at sea and a consequential reduction in time fishing of 0.44%. The increased time at sea incurs a further penalty, however, in reducing the total trips taken by 12.02%.

2.3.4 Wind farm comparisons – economic metrics

Considerable differences were found when comparing economic metrics (fleet revenues, total costs, average total costs, and average fuel costs) between business-as-usual (Q500) scenarios and those with wind farms (Figure 7, Table A.2, Table A.6). All percentage values represent the range of economic metrics across all five ocean quahog penalty cases for one wind farm designation. Across all simulations, total revenues declined as wind farm restrictions increase. This outcome is consistent with the reduction in the number of trips taken and the increased time at sea per trip. Cases with transit and fishing restrictions in current and future wind farms produced reductions in revenue from 7.17-17.85% compared to cases without wind farms, whereas less severe cases with transit allowed and only fishing restricted in current leases resulted in a reduction in revenue of 0.86-2.73%.

Average total cost per cage landed for the fleet increased in every scenario except Q01T, in which costs decreased by 0.24%. The largest average total costs were found in 2N cases (1.90-6.86% - excluding Q6, see Figure 7) followed by 1N (2.01-2.72% - excluding Q6, see Figure 7). Rising costs reflect boats needing to spend more time at sea. The same trends were identified regarding average fuel cost per cage landed. Scenarios without transit (1N, 2N) displayed the highest average fuel costs (1N: 4.44-8.15% - excluding Q6, see Figure 7, 2N: 4.05-15.80% - excluding Q6, see Figure 7) which increased where costs were higher under future wind development. Total fleet costs – which include vessel operational costs - always decreased. Across all scenarios, total costs were lowest among 2N and 2T in accordance with these cases also being characterized by the largest decrease in number of trips.

2.3.5 Landings

The highest landings were associated with the Q0 cases, followed by Q3, Q4, Q5, and Q6 (Figure 8, Table A.7). In each set of simulations, an increment in the penalty imposed by ocean quahog overlap reduced total landings. In each set of simulations aside from the Q6 series, landings declined once wind farms were added and were further reduced when the wind farm footprint increased. Cases with no transit produced lower landings than those with transit allowed. Interestingly, scenarios with the highest average landings, Q0, exhibited the greatest declines once wind farms were added to the simulations, a loss of 500,000 bushels landed annually between cases Q000 and Q02N. Total annual landings losses for the remaining cases are: 250,000 bushels (Q500 – Q52N, Q300 – Q32N), 200,000 bushels (Q400 – Q42N), and 50,000 bushels (Q600 – Q62N). Landings are further reduced across all cases when transit within wind farm leases is restricted, and again the greatest declines occur in cases with the lowest quahog penalty (Figure 8, Table A.7). Q6 cases are somewhat of an anomaly because the addition of leases did not substantively reduce landings. The effect of the ocean quahog mask overwhelmed any influence of the loss of TMSs due to wind farms.

2.3.6 Spatial displacement in catch

Catch was displaced spatially amongst scenarios with displacement varying between the extent of lease development and ocean quahog penalty (Figures 9-11, Figures A.1-A.2). Changes in fishing catch in this analysis occur primarily in waters off of Long Island and New Jersey, which coincide with current and future wind farms, and with the portion of the fishery found to be most impacted by restrictions due to wind farms. In cases with transit allowed, but no fishing (Figures 9-11a,c), catch displaced to TMSs adjacent to leases both inshore and offshore. If transit through wind farms was not allowed, catch was mainly displaced nearshore and to the north (Figures 9-11b,d) as these TMS were most easily accessible to vessels and minimized time at sea. Comparing cases with current lease development (1N, 1T) with those with current and future lease development (2N, 2T) (Figures 9-11a,b vs. Figures 9-11c,d) fishing catch was displaced inshore off of New Jersey and to the south off the Delmarva Peninsula.

Similar trends in catch displacement are also seen in scenarios with different penalties due to ocean quahog overlap (Figures 10-11, Figures A.1-A.2). Note that no TMSs are closed in Figure 9 (Q0) due to ocean quahog overlap, and vessels are able to fish further offshore and to the south. As wind farms are added and transit is restricted, catch is again shifted to northern inshore areas. Little difference is observed between simulations with reduced ocean quahog penalties (Q3, Q4). In a few TMSs, mostly south of New Jersey, catch increased in Q3 (S6) in comparison to Q4 (S7), likely due to greater landings in masked ocean quahog TMSs. This trend is exemplified when comparing Q3 and Q4 to the Q5 simulations that have a higher ocean quahog penalty. Catch amongst Q3 and Q4 cases is spread more evenly across the domain. Maps of catch displacement for Q6 scenarios show a vastly reduced area of available fishing grounds (Figure 11). Once again, the same trends are observed. However, catch is condensed into just a few TMSs off of New Jersey as vessels have little option to choose from when fishing.

2.4 Discussion

2.4.1 Perspective

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

2.4.2 The odd interaction of wind farm leases and ocean quahogs

In comparison to the business-as-usual cases (Q5), namely the simulations including wind farms and the present-day fishing limitation imposed by ocean quahog overlap, simulations with no ocean quahog penalty (Q0) but with wind farms routinely displayed the highest reductions in revenue and total trips as well as the largest increase in average total costs and fuel costs ($US/cage). In scenarios with a less restrictive ocean quahog penalty – Q3 (30%) and Q4 (40%) – revenues declined while costs rose, but to a more sizable degree in Q3. Put another way, cases with a less restrictive ocean quahog penalty (Q0, Q3, Q4) tended to show a greater and more negative economic impact with added wind farms compared to the more restrictive cases (Q5, Q6). In Q5 and Q6, fishable area is already greatly reduced due to ocean quahog penalties. The addition of wind farms does further constrain the available fishing footprint, but does not have as sizable of an impact compared to the less restrictive ocean quahog penalty cases in which a greater reduction in spatial footprint occurs with wind farms added. Also, in these less restrictive cases, inclusion of a larger wind farm footprint (2T,2N) produced greater economic impact than the more spatially limited wind farm footprint (1T,1N) compared to the more restrictive cases. While Q3 and Q4 exhibited similar trends in fishing and economic metrics, percent change in the 2T and 2N scenarios compared to 1T and 1N scenarios was greatest in Q3 followed by Q4. In these cases, less restricted fishing prior to wind farm implementation had a more substantial effect.

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

2.4.3 The sparing of wind farm effects by lowering ocean quahog penalty

These simulations explored the consequences of allowing landing both Atlantic surfclams and ocean quahogs by reducing or eliminating the handling penalty when fishing in overlap areas (Q4, Q3, Q0). When the handling penalty is reduced from 50% to 40% or 30%, landings improved by 50,000 to 150,000 bushels (respectively) regardless of restrictions due to wind farm development. Vessels in the raised penalty cases spent more time at sea transiting between port and fishing location as their available fishing domain was constrained due to the presence of ocean quahogs, reducing overall landings. However, landing losses between the no restriction (00) and most restrictive (2N) case are nearly equal (-250,000 bushels) in cases of 50%, 40%, and 30% penalties (Figure 8). Fishing metrics between Q5, Q4, and Q3 scenarios are relatively similar (Figure 4). It is possible that these cases did not produce any substantial variation in total landings from 00 to 2N because sufficient fishable area remained available to support the prior catch levels after wind farm emplacement; nevertheless, catch was retained at an economic penalty in these cases.

Patterns of spatial displacement in catch illustrate the complex interaction of wind farm siting and ocean quahog overlap on the surfclam fishery. Decisions of where to fish balance the limited time at sea to prevent spoilage, the need to achieve a sufficient LPUE to fill the vessel, and the need to maintain a schedule of approximately two trips per week (Munroe et al. 2022). The results show that as the geographic limitations of fishable bottom grow, the number of trips declines and the time at sea increases. Depending on the spatial footprint and level of restrictions in the wind farms and the handling penalty due to ocean quahog overlap, the fleet is displaced to the north, south, and/or offshore.

LPUE tends to be less impacted as the necessity of fishing a highly abundant TMS becomes even more paramount with increasing time at sea required to access TMSs farther from port. Vessels specifically target areas of high clam density, resulting less of an impact on LPUE, although the time to transit to these areas is greater as the TMS are further offshore. Nonetheless, the economic impact of a reduction in trips and higher costs due to increased time at sea is not overcome by higher LPUE and total landings decline notably as the ocean quahog penalty increases and the geographic footprint of the wind farms expands (Figure 7).

2.4.4 Climate change, multi-use management, and the future

The northwestern Atlantic is warming more rapidly than many areas in the world's oceans (Pershing et al. 2015, Friedland et al. 2020, Friedland et al. 2022) and marine heat waves are becoming more common (Laufkōtter et al. 2020, Trisos et al. 2020). Warming of the northwestern Atlantic and the consequent shift in Atlantic surfclam populations (Hofmann et al. 2018, Powell et al. 2020a) into cooler waters outside of their historical range creates new challenges in assessing the future of the Atlantic surfclam fishery. Spatial shifts in the Atlantic surfclam range further away from ports and processing facilities have already resulted in a movement of processing capacity (McCay et al. 2011) and a shift in vessels to more northern ports (e.g., DeGrasse et al. 2014). Hennen et al. (2018) documented the reposition of Atlantic surfclams away from their historical southern boundary through rapid mortality at the trailing edge and subsequent slower recruitment of the leading edge of the range in deeper waters. The potential limitation of food availability in deeper water remains an uncertainty (Hofmann et al. 2018) as benthic production appears to be an important component (Munroe et al.

2013) and lower surfclam condition offshore has been documented (Marzec et al. 2010). An imbalance between the rate of range contraction south and inshore and stock buildup north and offshore might be expected based on larval dispersion dynamics (Zhang et al. 2016) resulting in complex management challenges to ensure that the Atlantic surfclam fishery remains economically viable. Weather is also an important factor in determining success of the Atlantic surfclam fishery. High winds prevent vessels from making trips, while air temperatures can cause product to spoil on board (Munroe et al. (2022)). Climate change may increase the frequency and duration of weather events that impact the fishery, in turn impacting the profitability of the fishery. As vessels fish at greater distances from port, the influences of weather and temperature become even more important.

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

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

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

Subsequent to the model simulations in this paper and the two preceding similar studies (Munroe et al. (2022) and Scheld et al. (2022)), the Bureau of Ocean Energy Management released an updated version of their planned lease areas for the Outer Continental Shelf. Areas of proposed future wind energy development are reduced in size compared to the ones currently in SEFES simulations in some areas and expanded in size in others. It is unknown at this time how the changes in proposed lease areas will affect the results of this study. Furthermore, the potential exists for the continuing range shift of Atlantic surfclams to alter the impact of offshore wind energy development should farm siting occur in the anticipated direction of the shift in the species' range. The well documented trend in Atlantic surfclam range shift (Narváez et al. 2015, Hennen et al. 2018, Hofmann et al. 2018, Powell et al. 2019, Powell et al. 2020) suggests continued movement of the range of the clam offshore and north relative to many of the proposed wind farm leases. The spatial footprint of wind energy leases in the MAB is everchanging, and may ultimately extend or lessen the overlap between windfarms and the range of the Atlantic surfclam.

2.4.5 Summary

Mixed landing regulations for Atlantic surfclams and ocean quahogs limits fishing locations in the MAB to where both species can be sorted on-board the fishing vessel. As the Atlantic surfclam shifts its range into cooler waters north and offshore, the spatial footprint of overlap between surfclams and ocean quahogs increases. Wind energy development on the outer continental shelf further reduces fishable area as vessels may be prohibited from fishing or transiting within wind farm leases. SEFES, an agent-based model of the Atlantic surfclam fishery where agents are individual vessels in the fleet, was used to simulate various degrees of fishing constraints from species overlap and wind energy development. Lowering the ocean quahog penalty to allow for more on-board sorting time increases the raw catch numbers (up to 150,000 bushels annually) and annual revenue (up to 5.98%) compared to the current status of the fishery. The implementation of wind farms, especially in cases of no transit within leases, resulted in reductions of annual landings and revenues, and increases in time at sea and costs (including fuel costs). Model scenarios with a lower ocean quahog penalty also exhibited the greatest losses in revenue and landings and rising costs when wind farms were added to the simulations, compared to business-as-usual cases mimicking current fishery trends. This analysis demonstrates the impacts of climate-induced range shifts and wind energy development on the Atlantic surfclam fishery and the potential economic consequences the fishery faces as competitive use of the outer continental shelf escalates.

2.5 Tables

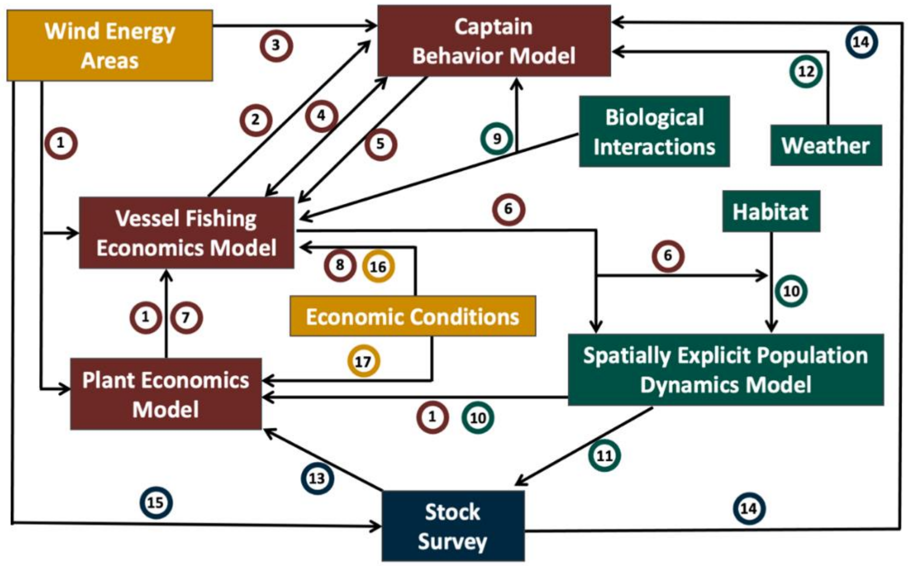
Table 2.1 *SEFES model scenarios with varied ocean quahog catch restrictions and associated penalties.*

Model Scenario	Description
Q5	Business-as-usual: standard fleet behavior; 50% quahog penalty = 1/6 of unmasked TMS
Q0	Quahog mask and penalty removed
Q3	30% penalty = 1/2 catch of unmasked TMS
Q4	40% penalty = 1/3 catch of unmasked TMS
Q6	100% penalty – zero catch efficiency in masked TMS

Table 2.2 *SEFES model simulations examined to determine impacts of ocean quahog overlap and wind farm placement on the Atlantic surfclam fishery*

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

2.6 Figures



Category	Component Processes	Property	Source
Fishery Processes			
1	Fleet dispersion	Location and movement	Fishery dependent data and stock assessment
2	Vessel characteristics: speed & capacity, dredge size & efficiency	Speed (knots), capacity (cages), dredge size (length), dredge efficiency (rate of catch)	Industry advice and stock assessment
3	Safe vessel operation	Subjective	Industry advice
4	Captain memory, searching & communication	Catch (LPUE) per TMS	Industry advice
5	Captain skill	Rate of catch	Industry advice
6	Fishing mortality (size-selective)	Rate of catch by size class	Stock assessment
7	Vessels in the fleet, quota allocation	Number and properties of vessels, and quota (bushels)	Industry advice and fishery dependent data
8	Port location	Location (TMS)	Fishery dependent data and stock assessment
Biological & Environmental Processes			
9	Species overlap – Atlantic surfclams and ocean quahogs	Location (TMS)	Industry advice and unpublished research data
10	Biological processes: recruitment, mortality, growth, yield	Recruitment (clams per m2), mortality (natural mortality rate), growth (shell size over time), yield (mass per size over season)	Industry advice, stock assessment, and unpublished data
11	Population structure	Length frequency and abundance by TMS	Stock assessment
12	Wind & temperature	Wind (miles per hour), temperature (° C)	Meteorological and airport records
Management Processes			
13	Quota, stock trends, & fishery independent data	Quota (bushels), trends (abundance and body size over time), fishery independent data (catch statistics)	Stock assessment, MAFMC 2020, research papers
14	Survey Report	Stock distribution and biomass by TMS	Stock assessment
15	Survey displacement	Location and movement	Advisor advice
External Forces			
16	Fuel & vessel costs	Rates	Industry advice and published prices (Energy Information Administration)
17	Wholesale value	Prices by product type	Industry advice

Figure 2.1 Diagram of interactions amongst components in SEFES: survey and management (blue), fishing industry (red), biological interactions including ocean quahog overlap (green), and external forces including wind energy areas (gold). Processes acting between components noted on black arrows and referenced in associated legend. Adapted from Munroe et al. (2022).

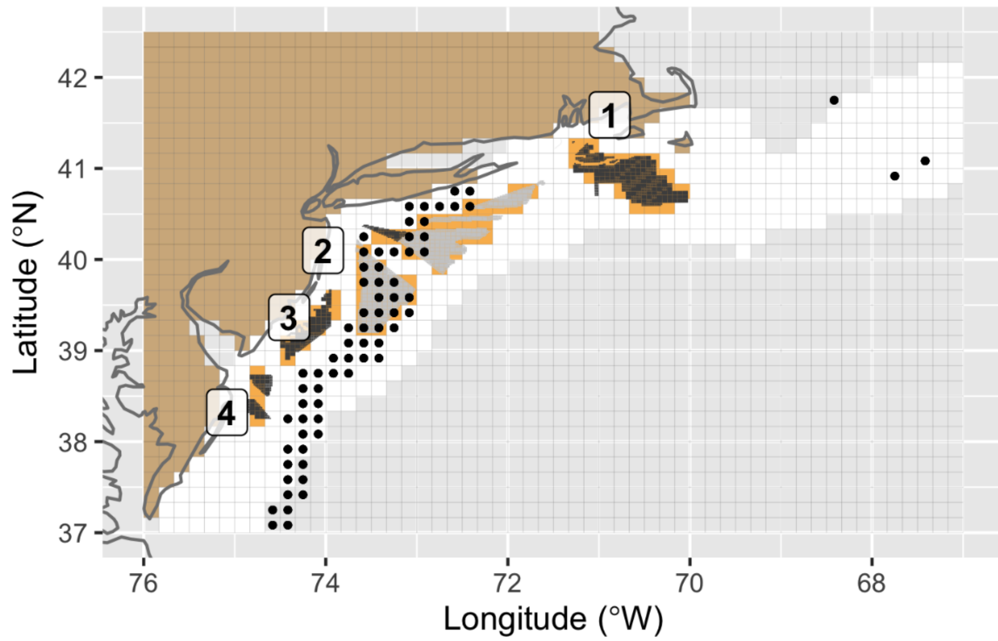


Figure 2.2 Map of SEFES model domain showing TMSs with ocean quahogs (black dots), wind farm leases (dark grey), potential future wind farm leases (light grey), and grid cells around leases with restricted fishing and transit (orange) Landing ports for Atlantic surfclam fishing vessels, from north to south are New Bedford, Massachusetts (1); Pt. Pleasant, New Jersey (2); Atlantic City, New Jersey (3); and Ocean City, Maryland (4). Figure adapted from Scheld et al. (2022).

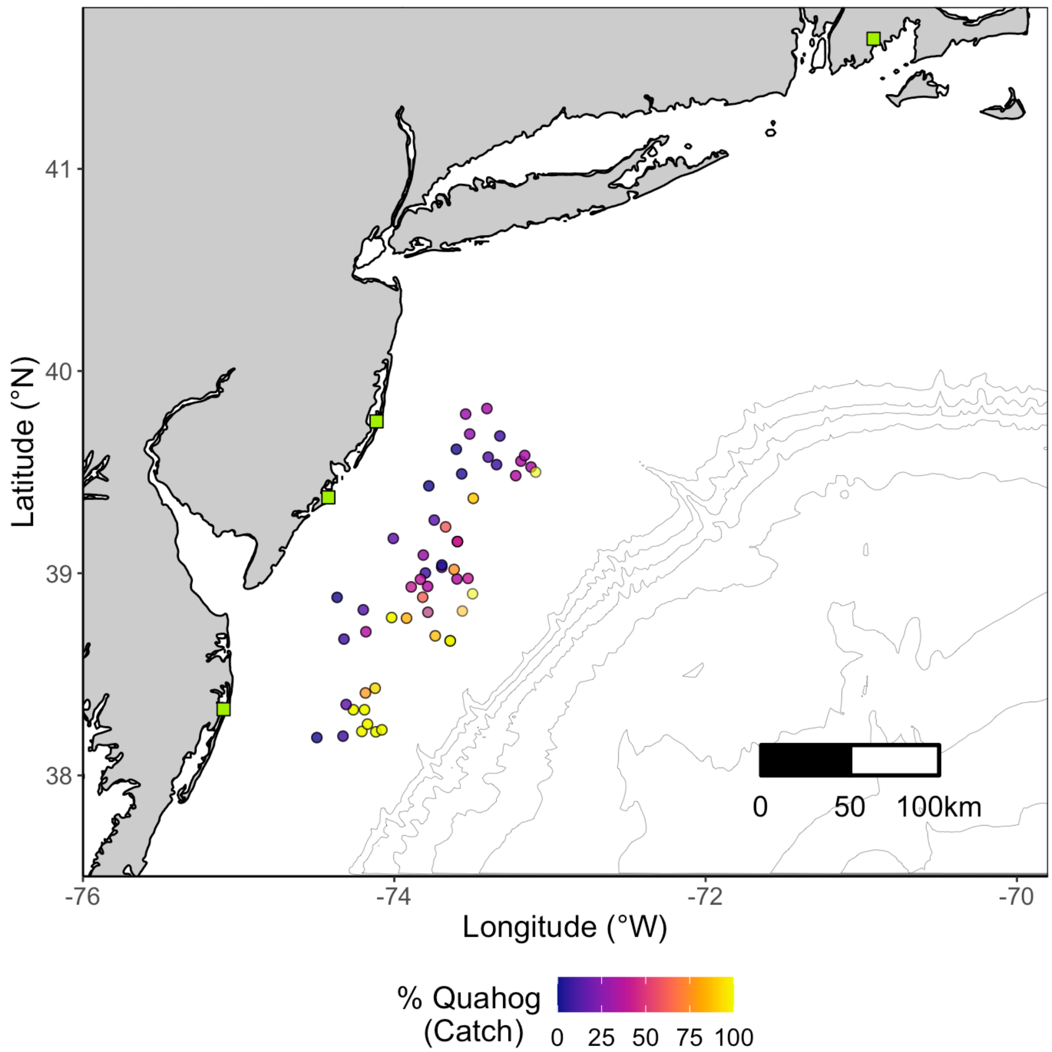


Figure 2.3 Atlantic surfclams and ocean quahog overlap from off northern Delmarva to Hudson Canyon as of September 2021. Dark blue circles indicate locations of 100% Atlantic surfclam catch. Yellow circles indicate locations of 100% ocean quahog catch. Intermediate colors on the gradient show regions of mixed catch of both species. Landing ports for Atlantic surfclam fishing vessels are specified by green squares, from north to south: New Bedford, Massachusetts; Pt. Pleasant, New Jersey; Atlantic City, New Jersey; and Ocean City, Maryland.

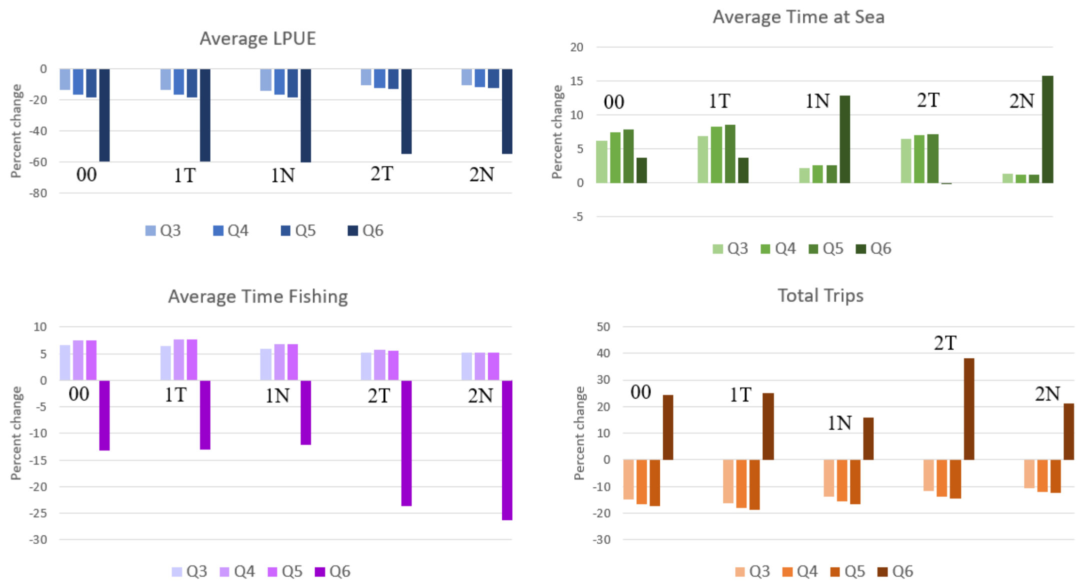


Figure 2.4 Percent change in fishing activity for each ocean quahog penalty case relative to the scenario without the ocean quahog catch penalty (Q0) grouped by wind farm designation.

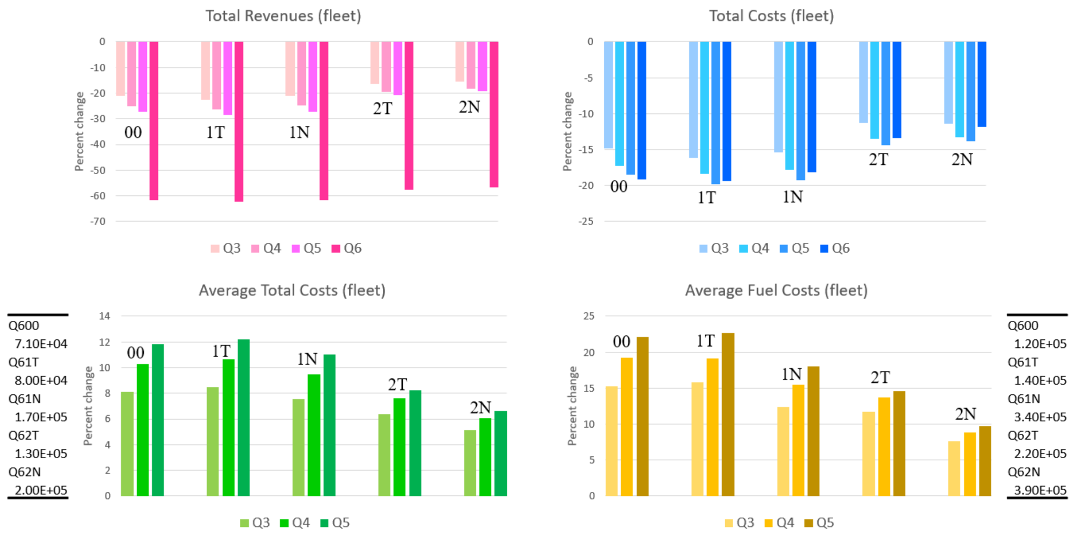


Figure 2.5 Percent change in economic metrics for each of the SEFES simulations relative to the case with no ocean quahog catch penalty (Q0) grouped by wind farm designation. Values for Q6 cases are shown in the table to the left and right of the plots respectively for Average Total Costs (fleet) and Average Fuel Costs (fleet), as they are much greater in scale. Average total costs and fuel costs are obtained by dividing totals by the number of cages landed (US$/cage). 1 cage = 32 bushels; 1 clam bushel = 53.2 L.

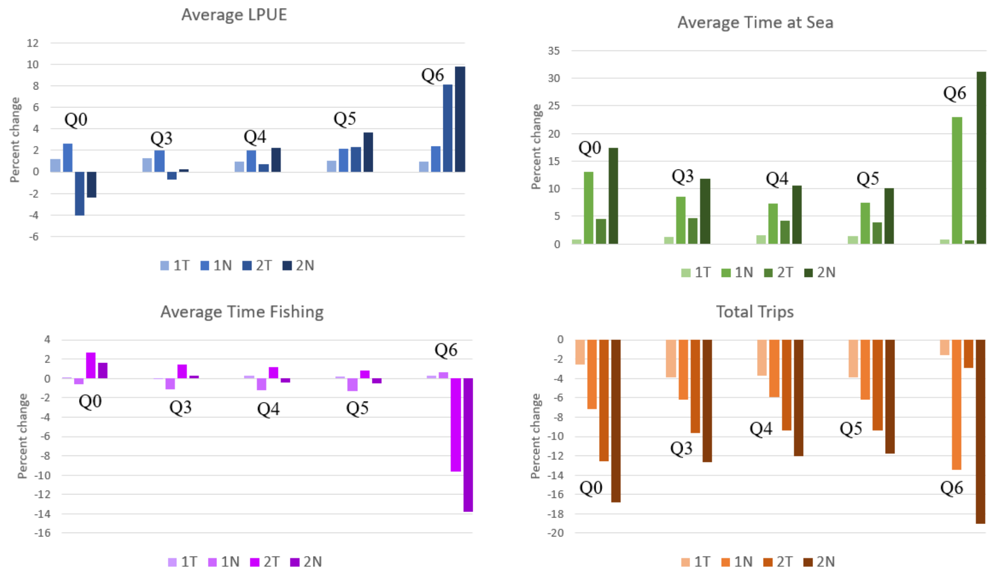
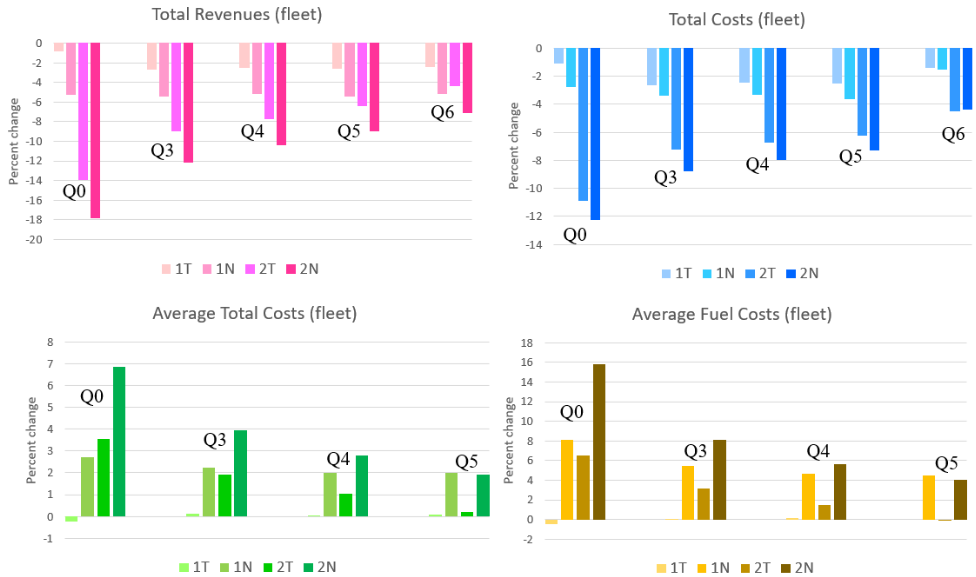


Figure 2.6 Percent change in fishing activity for each wind farm case relative to the scenario without wind farms (00) grouped by ocean quahog penalty.



Q61T	Q61N	Q62T	Q62N
11.68	142.07	90.65	207.33

Q61T	Q61N	Q62T	Q62N
12.56	195.57	91.77	270.28

Figure 2.7 Percent change in economic metrics for each wind farm case relative to the scenario without wind farms (00) for each set of simulations and grouped by ocean quahog penalty. Values for Q6 cases are shown in the table below the plot for Average Total Costs (fleet) and Average Fuel Costs (fleet), respectively, as they are much greater in scale. Average total costs and fuel costs are obtained by dividing totals by the number of cages landed (US$/cage). 1 cage = 32 bushels; 1 clam bushel = 53.2 L.

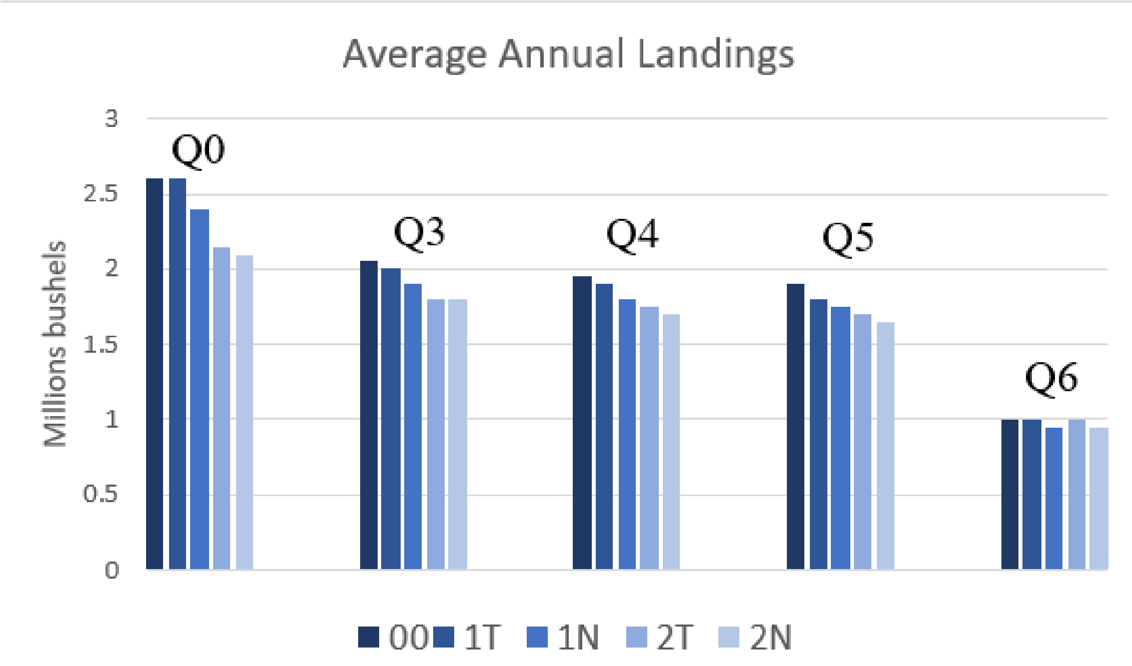


Figure 2.8 Average annual landings in millions of bushels for each SEFES case. Averages are determined across 200 simulations of each case and reported to the nearest hundredth.

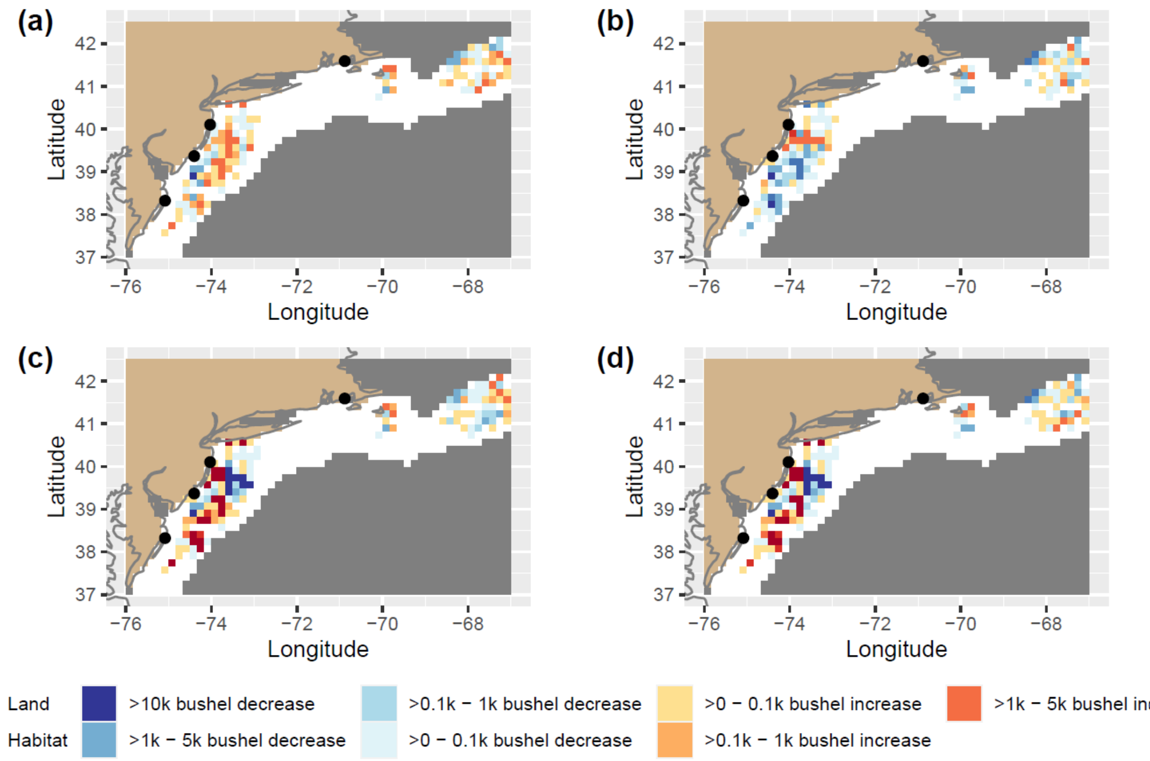


Figure 2.9 Spatial changes in catch, indicated by the change in catch per TMS per year, for each wind farm case as compared to the no ocean quahog penalty scenario without wind farms (Q000). (a) current leases with transit allowed, Q01T; (b) current leases with no transit, Q01N; (c) current and future leases with transit allowed, Q02T; (d) current and future leases with no transit, Q02N. Each TMS represents the difference of average catch in bushels for that TMS between specified cases. A decrease or increase in bushels indicates fewer or more landings, respectively, in that TMS.

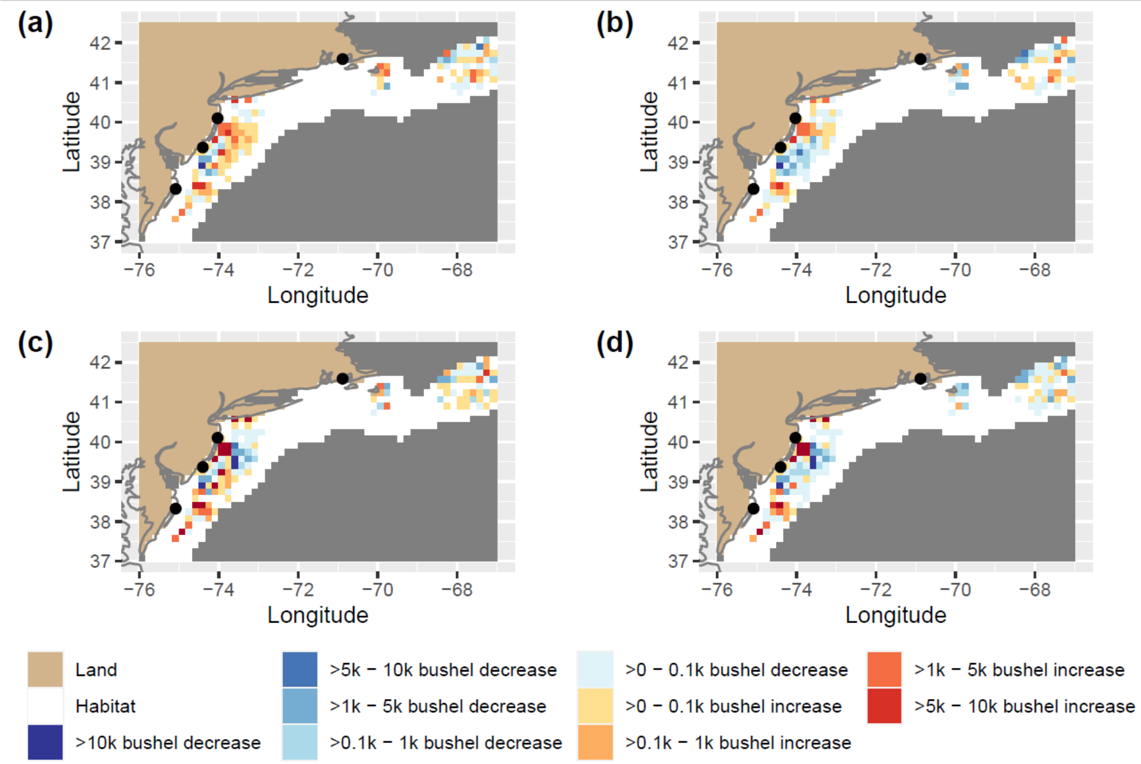


Figure 2.10 Spatial changes in catch, indicated by the change in catch per TMS per year, for each wind farm case as compared to the business-as-usual scenario without wind farms (Q500). (a) current leases with transit allowed, Q51T; (b) current leases with no transit, Q51N; (c) current and future leases with transit allowed, Q52T; (d) current and future leases with no transit, Q52N. Each TMS represents the difference of average catch in bushels for that TMS between specified cases. A decrease or increase in bushels indicates fewer or more landings, respectively, in that TMS.

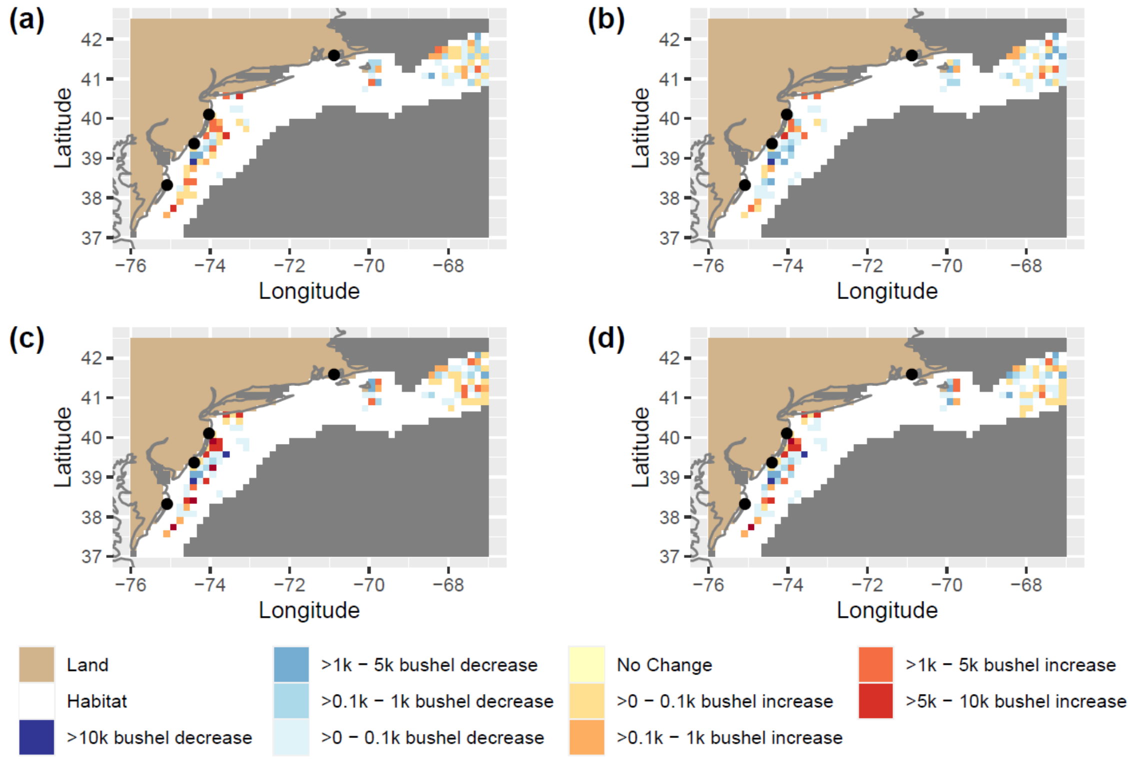


Figure 2.11 Spatial changes in catch, indicated by the change in catch per TMS per year, for each wind farm case as compared to the 100% ocean quahog penalty scenario without wind farms (Q600). (a) current leases with transit allowed, Q61T; (b) current leases with no transit, Q61N; (c) current and future leases with transit allowed, Q62T; (d) current and future leases with no transit, Q62N. Each TMS represents the difference of average catch in bushels for that TMS between specified cases. A decrease or increase in bushels indicates fewer or more landings, respectively, in that TMS.

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CHAPTER III – EVALUATION OF THE DEGREE OF CO-OCCURRENCE OF ATLANTIC SURCLAMS (SPISULA SOLIDISSIMA) AND OCEAN QUAHOGS (ARCTICA ISLANDICA) IN THE EXPANDING NORTHWESTERN ATLANTIC BOREAL/TEMPERATE ECOTONE: IMPLICATIONS FOR THEIR FISHERIES

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3.1 Introduction

The Northwest Atlantic Ocean is a bellwether of climate change, as its warming trends far exceed those observed throughout oceans around the world (Pershing et al. 2015, Kavanaugh et al. 2017, Seidov et al. 2021). Surface and bottom water temperatures in the Northwest Atlantic have risen on average 0.24°C per decade from 1968-2018 and 0.95°C per decade from 2004-2018 (Friedland et al. 2020). Rapidly rising temperatures are thought to stem from weakening of the Atlantic Meridional Overturning Circulation (AMOC) and a retreat of the Labrador Current, accompanied by a shift in the Gulf Stream, transporting warm, salty water northward and thus replacing cold Labrador Slope water along the continental shelf (Joyce & Zhang 2010, Zhang et al. 2011, Saba et al. 2016, Chen et al. 2021, Megann et al. 2021, Whitney et al. 2022). Modulation by the North Atlantic Oscillation (NAO), in which positive phases result in a northward shift of the Gulf Stream and westerly winds raising water temperatures in the mid-Atlantic, is also well described (Sha et al. 2015, Xu et al. 2015, Kavanaugh et al. 2017).

Two provincial boundaries exist on the northeast U.S. continental shelf. Cool temperate species inhabit the southern Virginian province while boreal species are found in the northern Acadian province (Hale 2010). Acadian province conditions advance southward into the Mid-Atlantic in the form of the Cold Pool, as a seasonal thermocline traps cold (<10°C) bottom water along the mid to outer continental shelf through much of the spring into the early fall (Houghton et al. 1982, Sha et al. 2015, Lentz 2017. Chen et al. 2018). The Cold Pool generates an unusual and extensive cross-latitude (N-S) provincial boundary distinctive from the typical cross longitude (E-W) boundary, the commonplace condition associated with most faunal provincial boundaries (Hutchins 1947, Briggs & Bowen 2012). Many demersal finfish and shellfish species and their fisheries are dependent on the setup of the Cold Pool (Colvocoresses & Musick 1984, Miles et al. 2021) for survival in the southernmost portion of their range.

The Atlantic surfclam (*Spisula solidissima*) is a biomass dominant, cool-temperate species of the northeast U.S. continental shelf. Prior to the 1970s, the range of the surfclam extended from Cape Hatteras to Georges Bank at depths of 10-50 m (Merrill & Ropes 1969, Palmer 1991, Powell et al. 2017) but warming bottom water temperatures have caused the Atlantic surfclam to shift its range to cooler waters north and offshore. This range shift is one of the most geographically extensive range shifts recorded in the North Atlantic (Weinberg et al. 2005, Hennen et al. 2018, Hofmann et al. 2018, Hornstein et al. 2018, Timbs et al. 2019, Powell et al. 2019, Powell et al. 2020a). Temperature-induced mortality in surfclams at the southern and inshore portions of their range occurs as respiration rate exceeds assimilation rate and scope for growth declines, decreasing condition and compromising energetics until death (Kim & Powell 2004, Marzec et al., 2010; Munroe et al., 2016). This range shift is well documented, beginning with the withdrawal of surfclams from shelf waters off Virginia and Maryland in the 1970s (Loesch & Ropes, 1977; Powell, 2003) and development of the surfclam fishery in New Jersey in the 1990s (NEFSC 2017a). A large mortality event occurred off the Delmarva Peninsula around 2000, followed by a decline in surfclams in New Jersey waters shortly thereafter (Kim & Powell 2004, NEFSC 2017, Hofmann et al. 2018). Surfclam populations have expanded into federal waters off Long Island and Georges Bank (Powell et al. 2020a), but aggregate trends have resulted in a contraction of the range of the Atlantic surfclam.

Another biomass-dominant clam species of the North Atlantic is the ocean quahog (*Arctica islandica*). The ocean quahog is a boreal clam with a range extension into the Mid-Atlantic Bight (MAB) courtesy of the Cold Pool (Miles et al. 2021), which expands the range of the ocean quahog into lower latitudes than defined by the nearshore boreal-temperate provincial boundary (Engle & Summers, 1999, Hale 2010). Ocean quahogs are most abundant at depths of 30-60 m in this region (Dahlgren et al. 2000) and have historically resided in waters offshore of those occupied by the Atlantic surfclam with relatively little overlap along the inshore range boundary (NEFSC 2017a,b), presumably due to the stability of the temperature gradient maintained by the Cold Pool. Species' onshore and southern range limits often are temperature-determined, as many marine species live under conditions near their upper thermal limit (Brandt & Wadley 1981, Woodin et al. 2013, Pinsky et al. 2019; but see Sirén & Morellli 2020), as is the case with surfclams (Narváez et al. 2015) and would be presumed for ocean quahogs; however, the inshore boundary of ocean quahogs has remained relatively stable despite rapidly warming temperatures, presumably due to their ability to burrow and estivate for extended periods (Taylor 1976, Oeschager 1990, Strahl et al. 2011), thereby avoiding the high temperatures in early fall as the Cold Pool breaks down. LeClaire et al. (in prep.) provide additional support in documenting the unusually slow rate of inshore range regression in ocean quahogs since the end of the Little Ice Age as a consequence of declining recruitment inshore but centurial survival of older animals under warming conditions.

An ecotone is defined as a boundary transitioning between neighboring ecological systems over a wide range of space and time (Gosz 1993). The historically narrow ecotone cross-shelf between Atlantic surfclams and ocean quahogs has broadened in scope in the past decades due to the offshore range expansion of the surfclam into the inshore portion of the range of the ocean quahog (Powell et al. 2020b) sans any obvious regression of the inshore boundary of the ocean quahog. Typically, three outcomes of range shift interaction between two species exist: the presence of transient multiple stable states (Powell et al. 2019), direct competition resolved by some limiting resource (Peterson 1980, Peterson & Andre 1982), and cases where no major interactions between the two species are observed. One might hypothesize that the third option is true for Atlantic surfclams and ocean quahogs, as both species inhabit overlapping portions of their respective ranges but, thus far, have not been known to interact.

Regulations currently prohibit commercial fishing vessels from landing Atlantic surfclams and ocean quahogs as a mixed catch. This regulation was promulgated after the implementation of the Atlantic surfclam and ocean quahog individual transferrable quota (ITQ) system in 1990 (McCay et al. 1995) at a time where the ecotone between Atlantic surfclams and ocean quahogs was not spatially extensive nor well-documented. An amendment to the Atlantic surfclam and ocean quahog Fisheries Management Plan was made effective in April 1993, rendering any fishing or landing of surfclams and ocean quahogs on the same trip illegal (Anonymous, 1993). The ruling also prohibits any commercial vessel from landing surfclams on a designated ocean quahog fishing trip, or landing ocean quahogs on a designated surfclam fishing trip. The amendment was proposed to simplify the tracking of landings and limit illegal harvesting but, as a consequence, the regulation also limits harvest from fishing locations to where surfclams and ocean quahogs can be sorted by hand on deck, with the non-target species discarded. Industry guidance puts the amount of mixing deemed sortable on board at one individual of a non-target species in every 25 total clams, or 4% of the total catch (Stromp et al. in press).

Warming of the Northwest Atlantic has required substantial adaptations by the regional fishing industries in such core characteristics as vessel homeport and vessel size distribution (Young et al. 2019). Atlantic surfclams and ocean quahogs are both vital species to the economic success of Mid-Atlantic fisheries, producing a combined $53.6 million in ex-vessel annual revenue (Murray 2016) and are identified as species sensitive to climate change, with range contraction judged likely (Weinert et al. 2021, Coro et al. 2016). The minimal species overlap present throughout much of the history of the fishery produced a *de minimis* economic impact while generating a fishery with a renowned low level of bycatch discards. This latter record has degraded dramatically in recent years as the continual range shift of Atlantic surfclams offshore jeopardizes both the profitability of the fishery by restricting access to a shrinking region of the Atlantic surfclam stock (Stromp et al. in press) and the record of minimal discarding.

This study examines the developing ecotone between Atlantic surfclams and ocean quahogs. A research survey sampled locations in the MAB in September 2021 and identified further areas of overlap between the two species, extending the known range of the ecotone. Results of the ecotone analysis reported here map offshore surfclam expansion, as evidenced by juveniles and small size class individuals in deeper, coolwer waters and provide a detailed look at the differences in population demographics between these two species within what may be the most geographically extensive ecotone produced by global warming in the oceans.

3.2 Methods

3.2.1 Sample Collection

Atlantic surfclam and ocean quahog abundance, density, and size data from this study were gathered from an at-sea survey of the Mid-Atlantic outer continental shelf on the *F/V E.S.S. Pursuit* in September 2021. The cruise plan was designed using information from surfclam and ocean quahog fishing-vessel captains who relayed locations of high overlapping densities of surfclams and ocean quahogs, augmented by recent (2016-2018) NMFS survey data (NEFSC 2022). This information suggested a central tendency for species overlap in the 40-50-m depth range, deeper in the south than in the north. The cruise track consisted of transects oriented perpendicular to the depth gradient from inshore (~35 m) to offshore (~60 m) so that the most inshore location had surfclams only and the most offshore stations had ocean quahogs only. The cruise track oriented the transects at an angle so that the boat zig-zagged through the region to limit time lost in steaming between stations.

A total of 117 tows at over 50 stations were taken on this cruise, with sampling locations ranging from offshore Ocean City, Maryland to Hudson Canyon. A standard hydraulic clam dredge was used, the performance of which has been examined by Poussard et al. (2021). Further characteristics of this gear can be found in Meyer et al. (1981) and Parker (1971). Two tows were completed at most stations with differing bar spacing on the dredge. The surfclam dredge (indicated as the port dredge P in this analysis) operated with a bar spacing of 1.5" (3.8 cm) and a knife depth of 4.5" (11.4 cm). The ocean quahog dredge (identified herein as the starboard dredge S) utilized a slightly smaller bar spacing of 1.25" (3.2 cm) and a knife depth of 4" (10.2 cm). The use of two dredge designs permits a performance comparison between the two dredges styles with respect to species selectivity for Atlantic surfclams and ocean quahogs. On-board analysis included the number and size (in mm) of clams of the two target species, the GPS-measured tow length (decimal degrees latitude and longitude), and depth of each tow (m).

3.2.2 Statistical Analyses

Post-cruise, Atlantic surfclams and ocean quahog catch data were sorted into size classes of 10-mm increments between 30-200 mm. Degree of species overlap was adjudged relative to the assumption that sorting between the two species during commercial operations is not feasible if more than 4%, or 1 clam of the mixing species in 25 total clams (e.g., >1 ocean quahog in every 25 clams), of the non-target species was present in the dredge haul (Stromp et al. in press). Eleven summary statistics (referred to in analysis as size variables) were calculated for Atlantic surfclams and ocean quahogs in each tow and supplemented with environmental data (referred to in analysis as environmental variables) (Table 1). Temperature data were obtained from the Regional Ocean Modeling System (ROMS) implementation Doppio (López et al., 2020) and incorporated into the dataset as an average of mean September temperatures from 2016-2019. Temperatures from 2020 and 2021 were not available at the time of writing. The clam densities for each tow were not corrected for dredge efficiency or dredge selectivity. An estimate of dredge efficiency is provided in Poussard et al. (2021) and estimates of dredge selectivity are provided in NEFSC (2017b) for the ocean quahog dredge. Estimated landings per unit effort (LPUEs) are specified in cages hr^{-1}, 1 cage = 32 surfclam bushels (1 bushel = 53.2 L) and are based on the following assumptions: tow speed 3.1 knots; dredge time on bottom 50 min hr^{-1}; dredge width 3.048 m; dredge efficiency 1.0 as density estimates were not corrected for dredge efficiency. Dredge efficiency is likely around 70% (Poussard et al. 2021).

Unless otherwise noted, evaluation of the distribution of Atlantic surfclams and ocean quahogs was performed using statistical software R (vers. 4.2.1; R Core Team, 2022). All statistical methods presented were completed separately for Atlantic surfclams and ocean quahogs. Eleven type III SS ANOVAs were run for each species to analyze main effects and interaction effects for each size variable (as dependent variables) with the environmental variables (as continuous independent variables) in Table 1, totaling 22 ANOVAs for both species. Interaction terms Temperature*Depth, Depth*LPUE, and Temperature*Latitude were added. Dredge type was included as a factor.

Principal component analysis (PCA) was conducted for size and environmental variables for both species, totaling 4 PCAs. Each variable was scaled to a mean of zero and a standard deviation of 1, and the PCA displayed utilizing varimax rotation. A scree plot was used for each PCA to determine the number of significant axes (significance = >10% of variation). Significant PCA axes were then plotted against one another to determine how the variables are influenced by other variables of the same type (size or environmental).

Factor scores of significant axes from the size and environmental variable PCAs were then applied to Type III SS ANOVAs with significant size variable factors dependent variables and significant environmental variable factors as independent variables. Dredge type was not included in the PCAs and ANOVAs with PCA factors. Density and LPUE are perfectly collinear and thus grouped together for this analysis. Pearson's correlation coefficients were calculated for all significant interactions between size and environmental PCA factors to determine the intensity of correlation between PCA factors.

Correspondence analysis (Clausen 1998) was used to compare both size and environmental variables for the two species. All continuous variables were classified into thirds by the 33rd and 67th percentile with lower values and higher latitude designated as 1, higher values and lower latitude as 3, and middle values and latitude as 2. Dredge type was included as a supplementary variable and did not influence the axes in the correspondence analysis.

3.3 Results

3.3.1 Atlantic Surfclam and Ocean Quahog Overlap

Figures 1 and 2 display the estimated density of ocean quahogs and Atlantic surfclams, respectively, at each sampled station[1]. For context, see stock-wide distributional maps in NEFSC (2017a,b). The two species occur in high densities over much of the overlap zone. The largest catches of ocean quahogs occurred in deeper waters between 40 and 60 m. Atlantic surfclams were caught at depths of 30–60 m but were most abundant between 45 and 50 m.

Figure 3 shows the distribution of stations allocated to 4 groups defined by percentage of species overlap. Green boxes offshore indicate sampling sites where more than 24 of every 25 total clams (<4% mixing) was an ocean quahog. In most cases, these tows exclusively caught ocean quahogs. Stations with majority ocean quahog catch occur in the 55-60-m depth range; ocean quahogs are found at deeper depths, but this depth range was not sampled in the survey. Pink boxes are inshore locations where more than 24 out of every 25 total clams (<4% mixing) were Atlantic surfclams, with most tows catching exclusively surfclams. Stations with majority Atlantic surfclam catch occur in the 30-40-m depth range; analogous to ocean quahogs, surfclams are found inshore of this depth range, but these shallower depths were not sampled on the survey. Yellow and brown boxes indicate regions of overlap between the two species. Yellow boxes are stations where between 1 and 12 of every 25 total clams (4-50% mixing) was an ocean quahog, although the majority caught were surfclams. Brown boxes indicate stations where between 1 and 12 of every 25 total clams (4-50% mixing) was an Atlantic

[1] Post-cruise report and associated data are available at https://scemfis.org/shellfish-publications/

surfclam, although the majority caught were ocean quahogs. Both of the station types yielding mixed catch occupy a substantial region between 40 and 55 m with the surfclam-rich stations lying somewhat inshore of the ocean-quahog rich stations. For purposes of data presentation hereafter, the depth range of 40-55 m will be referred to as the region of overlap between Atlantic surfclams and ocean quahogs.

Stations were grouped together by tow depth in depth intervals of 2 m from <32 m to 46 m and in intervals of 5 m at deeper depths as fewer tows were taken at these deeper depths. The average density, LPUE, maximum size, and mean size of Atlantic surfclams and ocean quahogs was then calculated for each depth interval (Figures 4-7). Stations less than 40-m depth were dominated by Atlantic surfclams while those 50+ m contained high densities of ocean quahogs (Figure 4). The highest ocean quahog LPUEs (2.5-3 cages hr^{-1}) are found at the deepest sampled stations, while the highest values of LPUE for Atlantic surfclams (1.5 cages hr^{-1}) occur at 35-50-m and decline with increasing depth (Figure 5). Clam densities and LPUEs at depths of 40-55 m show a transition between surfclam-dominance and ocean-quahog dominance, further defining the center of the species' overlap as located within the 40-55-m depth zone.

Maximum size for ocean quahogs remained constant at 110-120 mm across the sampled region, whereas the largest Atlantic surfclams declined from 170 mm at 32-m depth to 120 mm at 60-m depth (Figure 6). The maximum size in surfclams was reduced by 30 mm over the overlap depth of 40-55 m. Trends in mean size of both clam species were similar to the trends for maximum size. The mean size of ocean quahogs fluctuated little across depth intervals, from slightly below 90 mm to 110 mm (Figure 7). Mean surfclam size declined from 145 mm at 32 m depth to 90-100mm at >50 m. Surfclam size declines gradually down to 40 m, then more sharply down to 55 m, with a loss in size of 30 mm over the overlap region.

Sampled stations were also grouped together by their mean September monthly temperature from 2016 to 2019. Tows were divided into 0.25°C intervals from <10.75°C to 13.5°C and into 0.5°C intervals from 13.5°C to >15.0°C, with the larger range being required by the fewer number of tows at higher temperatures. The mean density and size for Atlantic surfclams and ocean quahogs was calculated for each temperature interval (Figures 8-9). Mean surfclam density varied minimally from 0.1–0.3 clams m^{-2} across the temperature range, while ocean quahog density differed greatly between intervals (Figure 8). The majority of high ocean quahog densities greater than 0.3 clams m^{-2} were found at temperatures below 12°C (with the exception of the 14.5-15°C interval). The majority of intermediate densities of ~0.2 clams m^{-2} were found between 12-13.5°C and the majority of low densities 0.1 clams m^{-2} or less occurred at higher temperatures. Although Atlantic surfclam densities remained relatively constant across the temperature range, mean surfclam size increased with increasing temperature from 90 mm at <11°C to 140 mm at >15°C (Figure 9). Mean ocean quahog size, unlike density, only differed from 90-110 mm across the entire temperature range and displayed no obvious pattern with increasing temperature.

Tows were also grouped by latitude in 0.25° intervals from <38.25° to 39.75°, spanning the entire geographic range of the survey (Figure 10). Atlantic surfclam and ocean quahog mean sizes were calculated for each interval of latitude. Mean ocean quahog size increased with increasing latitude, from 90 mm at the most southerly latitude to 110 mm at the highest latitude. Atlantic surfclam mean size fluctuated from 115 mm to less than 130 mm across latitude, decreasing only slightly in the highest latitudinal intervals.

3.3.2 Analysis of Variance (ANOVA)

ANOVA results show that the distribution in size of Atlantic surfclams is primarily determined by depth followed by temperature, density/LPUE, and the depth*density interaction (Table 2). Depth is significant for all size variables with the exception of minimum size and kurtosis. Minimum size of surfclams did not show any significant trends amongst environmental variables or interaction terms. Distribution in ocean quahog size is explained by temperature, latitude, and the temperature*latitude interaction (Table 3). Temperature, latitude, and the temperature*latitude interaction are significant for all size variables except the 75th percentile, skewness, and kurtosis (with the addition of maximum size for latitude). Skewness and kurtosis in ocean quahogs did not show any significant trends amongst environmental variables and interaction terms. Dredge type is significant in only two ANOVAs: size range in surfclams and interquartile range in ocean quahogs. ANOVAs using density as a dependent variable resolved a significance depth effect for both Atlantic surfclams and ocean quahogs, with a significant depth*temperature interaction also present for ocean quahogs.

3.3.3 Principal Component Analysis (PCA) and Analysis of Variance (ANOVA) with PCA Factors

Principal component analysis (PCA) on Atlantic surfclam environmental variables yielded three factors that garnered 95.47% of the variation in the data (Table 4). Density/LPUE fell on factor 1, which explained 45.25% of the variability in the data. Temperature and depth fell on factor 2, explaining 34.95% and latitude on factor 3, accounting for an additional 15.27%. The Atlantic surfclam PCA for the size variables also resulted in three significant factors producing 92.01% of the variation (Table 5). Factor 1 contained variables of central tendency – mean and median size, 25th and 75th percentile, and skewness all explaining 59.69% of the variability in the data. Factor 2 is described by range variables – range, interquartile range, and minimum and maximum size accounting for 20.41% of the variation in the data. Factor 3 is defined exclusively by kurtosis encompassing 11.91% of the variation.

Principal component analysis performed on ocean quahog environmental variables resulted in two factors that amassed 83.21% of variance in the data (Table 6). Factor 1 includes density/LPUE, depth, and temperature, explaining 62.49% of the variation. Factor 2 is described by latitude accounting for 20.72% of the variation. The ocean quahog PCA on size variables yielded three significant axes encompassing 90.37% of the variation (Table 7). The variables corresponding to each axis are identical to that of the PCA for Atlantic surfclam size variables, with factors 1-3 explaining 50.84%, 25.73%, and 13.80% of the variation respectively.

ANOVAs were conducted using PCA size factors as dependent variables and PCA environmental factors as independent variables. All three environmental factors (PC1, PC2, and PC3) were found to be significant for size factor 1 in Atlantic surfclams (Table 8). Factor 1 comprises sizes of central tendency: mean, median, 25th percentile, 75th percentile, and skewness and PCAs representing density, depth, temperature, and latitude all had significant explanatory power for the size metrics. Latitude (PC3) was the only significant environmental factor for size factors 2 and 3. Factor 2 includes size measures of range: interquartile range, range, minimum and maximum size. Factor 3 includes only kurtosis. Pearson's correlation coefficients were also calculated for each significant relationship between size and environmental factors. All environmental factors were negatively correlated with size variables in factor 1. Latitude was positively correlated with size variables in factors 2 and 3.

Ocean quahog environmental variables were divided between two factors: PC1 (density/LPUE, temperature, depth) and PC2 (latitude). PCA factors for size variables comprised the same variables as Atlantic surfclams, described in the previous paragraph. PC1, representing density, depth, and temperature, was significant for size variable factors 1 and 2, with a positive Pearson's correlation for both (Table 9). PC2 was the only significant environmental variable for factor 3, with a weak negative correlation.

Size variables for central tendency were significantly related to density, depth, and temperature for both species. Kurtosis was significantly related only to latitude in both species. Size metrics relating to the range of sizes differed in their relationship to environmental variables for the two species, with latitude relevant for surfclams and density, depth, and temperature for ocean quahogs.

3.3.4 Correspondence Analysis

Correspondence analysis was conducted on Atlantic surfclam and ocean quahog datasets, including both size and environmental variables, to determine the relationships between and within variables. Many Atlantic surfclam categories with a 1 (smallest values) are grouped together on axis 1 in the upper right quadrant, including mean (MEAN1), median (MED1), maximum (MAX1), 25th (25PCT1) and 75th percentile (75PCT1), interquartile range (ITQ1), and range (R1) (Figure 11). The smallest surfclam size categories are accompanied by categories of lowest latitude (L3) and deepest depth

(D3), and to a lesser extent lowest density (DEN1). Intermediate surfclam sizes (2) align with axis 2, close to environmental categories of intermediate depth (D2), density (DEN2), latitude (L2), and temperature (T2). The largest size values for Atlantic surfclams lie between axes 1 and 2 in the upper left quadrant and are accompanied by categories of shallow depth (D1) and high temperature (T3).

Ocean quahog correspondence analysis places the largest clam sizes on axis 1 along with high latitude L1, but not with any categories of temperature, depth, or density (Figure 12). The smallest ocean quahogs are located in the upper left quadrant and not found alongside any environmental variables. High density (DEN3), deepest depth (D3), and low latitude (L3), while not closely linked, are the nearest environmental variables to small clam sizes. Intermediate ocean quahog sizes lie on axis 2 between the lower two quadrants, aligned with low and intermediate temperatures (T1 and T2), intermediate latitude (L2) and density (DEN2). Low density (DEN1), shallow depth (D1), and high temperature (T3) correlate with small values of range (R1) and a large minimum size (MIN3). A key difference between the ocean quahog and surfclam correspondence analysis is the limited relationship of the environmental variables with metrics of the size-frequency distribution for ocean quahogs, compared to the much stronger association for surfclams.

In both correspondence analyses, the two dredge types fall close to 0 on both the x and y axes, indicating the limited impact of the differences in bar spacing and knife depth. The expectation that the differentials in dredge type might influence the catchability of small clams differentially is not well supported by this analysis, nor the earlier described results of ANOVA.

3.4 Discussion

3.4.1 Perspective

The Northwest Atlantic is warming faster than many of the oceans around the world (Pershing et al. 2015, Friedland et al. 2020, Friedland et al. 2022). In response to increasing bottom water temperatures, Atlantic surfclam populations are shifting into cooler waters north and offshore of their historical range (Weinberg 2005; Hennen et al. 2018, Hofmann et al. 2018) into the present range of the ocean quahog. The Atlantic surfclam fishery has already responded to spatial shifts in the range of the surfclam by moving processing plants and vessels to northern locations and ports (McCay et al. 2011, DeGrasse et al. 2014) and opening up areas previously closed to fishing (DeGrasse et al. 2014), but future success of the fishery may depend on regulatory reform permitting mixed landing of clam species and improved sorting ability of surfclams and ocean quahogs on deck or in the processing plant. This study emphasizes the broad distribution of overlap between the two species and highlights depth, particularly between 40-55 m, as a limiting factor in Atlantic surfclam size and density. Distribution of ocean quahogs, meanwhile, is dependent more on temperature and latitude. The results described in this analysis may provide insight as to how the two species continue to respond to climate change and strengthen the need for regulatory reform.

The case history considered here also offers a unique perspective into the dynamics of ecotones and range boundaries on species' population dynamics during a period of rapid climate change. Range boundaries have received considerable attention observationally (Cook et al. 1998, Baker et al. 2007, Troost 2010, Thorson et al. 2016, Reise et al 2017) and through modeling of dispersion and recruitment (Guo et al. 2005, Hughes et al. 2007, Berestycki et al. 2009), genetics (Ibrahim et al. 1996, Excoffier et al. 2009, Garnier & Lewis 2016), and bioenergetics (Parsons 1991, Thomas et al. 2016), but ecotones wherein species' range boundaries overlap have received much less consideration (Brandt & Wadley 1981, Zuschin & Piller 1997, Smith et al. 2000, Carney 2005), primarily due to the spatially limited region of overlap normally present between faunas. Rapid warming of the Northwestern Atlantic has provided unique examples of overlap between continental shelf faunas, presumably as a product of differential behaviors of species, permitting differential rates of range boundary shifts. Powell et al. (2019) provide one example, between blue mussels (*Mytilus edulis*) and Atlantic surfclams, where differential behaviors have created transient multiple stable points (see also a potential additional example for mussels: Jurgens & Gaylord 2016). Herein is examined a geographically much more extensive ecotone, occupied by two clam species belonging to the cool temperate and boreal faunas providing an unparalleled opportunity to study population dynamics within an ecotone consequent also of differential behaviors and thus differential rates of range shifting by the two species.

3.4.2 The developing ecotone between Atlantic surfclams and ocean quahogs

The ranges of the Atlantic surfclam and ocean quahog overlap in the surveyed region of the Northwest Atlantic at depths between 30-60 m, with highest mixing at 40-55 m. Clam density within this depth range shifts from predominantly Atlantic surfclam at depths <40 m to ocean quahog dominated at depths >45 m. While ocean quahog size frequencies remain relatively constant between 40-55 m, metrics of the Atlantic surfclam size frequency begin to decrease around 40 mm. The size and density trends are indicative of more larger surfclams at inshore sites and more smaller surfclams offshore. Surfclam size increases with temperature, while density is stable.

The warm-temperature range boundary for surfclams is well studied and clearly determined by the effect of high temperature on scope for growth (Munroe et al. 2013, Narváez et al 2015, Hornstein et al. 2018). The determining factors controlling the cool temperature range boundary are much less well defined. Statistical analysis lends weight to the expected importance of bottom water temperature as a determinant influencing the distribution of Atlantic surfclams and ocean quahogs along the ecotone boundary. Bottom water temperature (also determined by depth) is the primary factor in determining successful occupation by surfclams. Herein, the importance of depth per se is downgraded as both species live over a very wide depth range depending upon regional temperature gradients. Temperature was significant in ANOVAs for 8 of 11 surfclam size variables (Table 2). Surfclam density and the density*depth interaction affect the size range, interquartile range, and maximum size of surfclams indicating biological modulation of the size-frequency distribution. Principal component analysis further places density, depth, and temperature as explaining the majority of variation in sampled sites (Table 4) and correspondence analysis shows that smaller clams are found in areas of low latitude and greater depth consistent with cooler bottom water temperatures farther offshore, while larger clams inhabit shallower waters where the temperature is higher (Figure 11). The results shown in this study all support the expectation that range expansion at higher latitudes, lower temperatures, and greater depths should be characterized by a shift in the size frequency towards an increased presence of small surfclams.

The size differential across the shelf may accrue from differential age frequencies wherein an expectation of younger surfclams offshore due to more recent range expansion would be consistent with observation, but also feasible would be a slower growth rate due to cooler temperatures and lower food availability offshore. The two options cannot presently be discriminated and substantial information supportive of both interpretations is well documented (Powell et al. 2020a, Munroe et al. 2013). What is clear is the absence of dispositive information determining the characteristics of the offshore range boundary of this species. Dispersal potential is clearly not a determining factor (Zhang et al. 2016, Timbs et al. 2019). Temperature clearly is, but whether temperature is a direct determinant (e.g., slow growth) or a time-dependent modulator (clam age determined by elapsed time since favorable temperatures for recruitment began) or both remains a conundrum.

Ocean quahog distribution is more influenced by temperature and latitude. Seven out of 11 ANOVAs for ocean quahog size variables were significant for temperature, 6 for latitude, and 7 for the temperature*latitude interaction (Table 3). Large ocean quahogs exhibit a distinct correlation with high latitude, but not with other environmental variables (Figure 12). Ocean quahog correspondence analysis places the largest clam sizes on axis 1 along with high latitude, Small ocean quahogs also show a lack of clear relationship to environmental variables, supported by weaker correlations (Pearson's correlation coefficients, Table 9) between PCA size and environmental variable factors. In correspondence analysis, the smallest ocean quahogs are located in the upper left quadrant well separated from any environmental variable.

Two issues arise, an explanation for the position of the ocean quahog inshore boundary and an explanation for the latitudinal effect. Ocean quahog density decreases as temperatures reach 14°C, but their size varies little. The temperature effect is consistent with the known upper thermal tolerance of the species, wherein continuous exposure to 16°C or higher results in death. Temperatures this high are often observed in the fall when the Cold Pool breaks down, prior to winter cooling (Lentz 2017, Chen et al. 2018, Friedland et al. 2022). Ocean quahogs, given their ability to burrow into the cooler sediment and estivate during warmer months (Taylor 1976, Ragnarsson & Thórarinsdóttir 2002, Strahl et al. 2011), escape warming temperatures and so are found in high densities with little variation in size within their historically (1982 to present) occupied range. No evidence of range recession is observed since federal surveys began in 1982. Thus, surfclams and ocean quahogs differ substantially in their size frequencies within the ecotone when compared to their size frequencies in the core of their range. Moreover, ocean quahogs are found inshore of an expected range boundary determined by their known thermal tolerance. Thus, the inshore boundary for this species is likely a complicated outcome of the interaction of physical environmental and behavioral processes.

The latitudinal effect on ocean quahog size presents an even greater enigma as growth rates are known to respond positively and substantively to warmer temperatures within the thermal limits of the species (Begum et al. 2010, Pace et al. 2018), providing an expectation of larger animals to the south, which is not observed. Ocean quahogs are long-lived and many of the individuals in the study were born in the 19th century, including prior to the ending of the Little Ice Age. As a result, these older animals grew slower early in life and, thus, remain smaller than animals recruiting under the warmer conditions of the 20th century. Comparison of age frequencies from the Long Island continental shelf to southern New Jersey show that the age frequencies are enriched in older clams farther south, presumably due to differential recruitment trends during the 19th century (Pace et al. 2017, Hemeon et al. 2021, 2023, Sower et al. in press). As a consequence, a tendency exists for more small old animals to be present to the south.

3.4.3 Dredge performance

Typically, the surfclam fishery uses a dredge with a wider bar spacing and a differential knife depth compared to the ocean quahog fishery. Presumably, this might influence the size frequency of the catch. This study deployed two dredge designs varying by bar spacing and knife depth identified herein as the P or surfclam dredge and the S or ocean quahog dredge. The P dredge had a slightly wider bar spacing than the S dredge, 1.5” to 1.25”. Dredge type was only significant in ANOVA for 2 of 20 size variables for both species, size range in Atlantic surfclams and interquartile range for ocean quahogs. For both clam species, minimum size and the 25th percentile were lowest in the S dredge while the interquartile range was largest. The S dredge with narrower bar spacing, in conclusion, caught smaller individuals of both species and a greater range of sizes compared to the P dredge. The issue is important in that exclusion of small animals, recognizing the bias of small surfclams in the ecotone, would permit increased harvest of desired size classes while minimizing sorting and discarding on the deck. The influence of dredge design on selectivity of surfclams and other clam species is well known (Gaspar et al. 2003, Kim et al. 2005, Sala et al. 2007). The differential observed in this study is, however, not large; thus, the value of the differential between the two dredge designs tested in differentiating surfclams and ocean quahogs is limited.

Dredge efficiency did not vary between the two dredge styles, as inferred from the absence of a significant difference in density, nor was an influence of depth on dredge performance detected; both dredge types fell near the origin in correspondence analysis. A Wilcoxon signed rank test was performed comparing catch between paired tows, with the results ($p = 0.7894$) indicating the two dredges are not significantly different from each other. These results agree with Poussard et al. (2021) who found little effect of depth or species on dredge efficiency.

3.4.4 Mixed landings: is it feasible?

The future of the Atlantic surfclam fishery rests on the extent of the ecotone between surfclams and ocean quahogs and how the fishery can adapt to the increased probability of catching both species on the same tow. Both fisheries focus on clam patches yielding 32 bushels/hr or more. This is particularly important for surfclams, as ocean quahog densities are routinely well above this threshold, whereas this is increasingly not the case for surfclams (Timbs et al. 2019, Solinger et al. 2022). In this study, surfclam densities reaching this threshold were not at all uncommon in the overlap zone (Figure 5). Current industry advice puts the degree of mixing able to be sorted on-deck at no more than 1 ocean quahog in 25 total clams, or 4% of the catch. Stromp et al. (in press) evaluated scenarios of increased sorting capability (>4%) that resulted in improved landings of 50,000 – 150,000 bushels of surfclams annually. Landing both species together would prevent a loss in fishing grounds and reduce discards; however, a regulatory change would be required.

In 2016, a request was made to the Mid-Atlantic Fishery Management Council (MAFMC) by clam companies to amend the Atlantic surfclam and ocean quahog Fishery Management Plan (FMP) (MAFMC 2016). The industry suggested a fixed number of clams other than the target species be allowed in a cage and raised questions as to how to handle the non-target species. The MAFMC published a committee recommendations summary in December 2021 and were supportive of a management approach that would require manual on-board sorting and separation of clams by species into cages (MAFMC 2021). Long-term solutions, such as a research and development approach, would then be discussed by the Council. In October 2022, the MAFMC released a drafted amendment to the Atlantic surfclam and ocean quahog FMP that proposed modifications to regulations to allow for mixed catches on-board vessels. Four Alternatives were outlined, with the first as no action taken and no changes made to current regulations (MAFMC 2022). Alternative 2 proposed the creation of a new combined trip category allowing surfclams and ocean quahogs to be landed on the same trip, also requiring on-board sorting. Alternatives 3 and 4 also create the combined trip category, but would require mixing of clams within cages to be on only declared combined trips. Alternative 3 would require manually monitored landings and trips with the implementation of a new NOAA Fisheries sampling program, whereas Alternative 4 would require on-board electronic monitoring. A preferred Alternative has not been selected and reconsideration of options is ongoing at this writing.

The MAFMC organized public hearings in November 2022 to gather input on the proposed species separation amendment. No further information from the hearings or public comments nor updates from the MAFMC on the amendment were released at the time of this writing. A reasonable assumption is that changes to mixed landing regulations will occur, but many questions remain on the economic and biological impact of mixed landings. What this study shows is the magnitude of this problem. The overlap region, as defined in Figure 3 now covers a large fraction of the Mid-Atlantic continental shelf south of Hudson Canyon. Sufficient information is not available to permit a further evaluation to the northeast, though overlap regions almost certainly are present (Powell et al. 2020a) and comparison of the data presented herein with earlier survey data (e.g., NEFSC 2017a,b) demonstrates the accelerating expansion of this ecotone throughout the Mid-Atlantic region over the last vicennium.

The ability to land both surfclams and ocean quahogs will certainly increase the fishable footprint in the Mid-Atlantic, however the addition of other uses of the continental shelf must be considered. Atlantic surfclam fleets, in particular, may be displaced by growing wind energy leases (Borsetti et al. 2023, Munroe et al. 2022, Scheld et al. 2022, Stromp et al. in press) affecting profitability of the fishery. These leases are primarily, but not exclusively inshore of the ecotone described herein, so that the present surfclam fishable stock is being restricted both inshore and offshore by competition with other anthropogenic uses inshore and other biological realities offshore. This study attempts to provide understanding to future challenges of the Atlantic surfclam and ocean quahog fisheries in the face of climate change, by highlighting the extent of species overlap and emphasizing the priority for mixed landing reform.

3.5 Summary

Results of this study track the shift of Atlantic surfclams into deeper, cooler waters offshore and north of their historical range into areas currently occupied by ocean quahogs. Ocean quahogs, however, largely have not yet responded to warming temperatures or the introduction of surfclams, as inferred from an absence of a distinction in distribution between small and large ocean quahogs and their relationship to environmental variables, with the exception of latitude. An important question remains and that is to explain the cross-shelf extent of this ecotone. Historically, over the modern survey time period which began circa 1982 (NEFSC 2017a,b), these two species have had minimal overlap. Catching both species in quantity occurred rarely until well into the 2000s (e.g., NEFSC 1999, 2002). Why is the ecotone so expansive today; conversely, why was it so narrow previously?

The transgression of the Atlantic surfclam's range has likely been occurring for 4-5 decades (Hofmann et al. 2018), but was not well documented until after 2000 (Kim & Powell, 2004). A surfclam's lifespan can reach up to 30+ years, and most individuals spawn by age 1-2 (Chintala & Grassle 1995, Chute et al. 2016). Ocean quahogs are much longer lived (200+ years), take longer to reach maturity (Sower et al. 2022), but may recruit no less frequently (Weinberg 1999, Pace et al. 2017; Hemeon et al. 2021, 2023; but see Powell and Mann, 2005). Individual ocean quahogs alive at the time of this study were likely to have been alive in the 1970s when the Atlantic surfclam began its range shift. While surfclam populations can shrink and expand within years to shift the species' range boundary, decades may be required for ocean quahogs to respond similarly. Ocean quahog past range shifts have been documented (Powell et al. 2017, LeClaire et al. 2022), particularly as a result of the regression of the Cold Pool at the end of the Little Ice Age. In particular, LeClaire et al. (2022) documented the offshore range recession of ocean quahogs after the Little Ice Age, during which they were found well inshore of their present-day depth range, with the largest, oldest animals surviving inshore longest. This process of departing the inshore region took place over a centurial time frame, presumably because large animals were able to survive apparently lethal temperatures through estivation and thus live where they “should not be found”.

One might expect, as deduced from LeClaire et al. (2022), that ocean quahogs will slowly move offshore as the Northwest Atlantic continues to warm, but no response to temperature or the presence of surfclams has been observed thus far. Possibly, the present situation is in fact the typical condition that has existed since the end of the Little Ice Age. The last warm period of the 20th century prior to initiation of the federal survey in 1982 occurred in the 1930s-1940s. The eastern U.S. was relatively cold beginning during the 1950s and extending through the 1980s, at the end of which the present warming trend began (Nixon et al. 2004, Ouellet-Bernier et al. 2020). A 30-40 year period of stable or decreasing temperatures could easily have limited surfclam expansion sufficiently to permit a relatively stable and narrow boundary to form between the two species, as observed in earlier stock surveys, as this time scale would be consistent with the slow establishment of a stable inshore range boundary by the ocean quahog while limiting further recruitment by surfclams offshore. Under this hypothesis, the earlier adaptation of the fishery to the landing of the two species separately might be seen as a response to an unusual species’ distribution pattern rather than the commonplace and the present situation a more normal circumstance since the end of the Little Ice Age. One might consider that the apparent absence of obviously competitive interactions between the two species is consistent with the routine extensive intermingling of these species fostered by the dramatic differential in rate of response to temperature change as the species march across the continental shelf consequent of climate change. The study emphasizes the importance of the relative rates of transgression and regression of range boundaries by abutting faunas in determining the degree of influence of the ecotone between them on the benthic community structure of the continental shelf.

3.6 Tables

Table 3.1 *Size and environmental variables calculated for Atlantic surfclams and ocean quahogs in each tow. All size variables are in mm, with the exception of skewness and kurtosis (no units). P dredge = Atlantic surfclam dredge, S dredge = ocean quahog dredge.*

Size Variables	Environmental Variables
Mean Size	Depth (m)
Median Size	Temperature (°C)
25^{th} percentile	Density (clams/m^2)
75^{th} percentile	LPUE (cages/hour)
Range	Latitude (°)
Interquartile Range	
Maximum Size	Dredge Type (P/S)
Minimum Size	
Skewness	
Kurtosis	
Density	

Table 3.2 *P values from Type III SS ANOVA conducted on Atlantic surfclam size variables as dependent variables and environmental variables and interaction terms as independent variables. Only significant ($p < 0.05$) results are shown, non-significance is denoted by a dash (-).*

Size Variables	Depth (m)	Temperature (°C)	Latitude (°)	Density/LPUE (clams/m^2)	Dredge Type	Temp.*Depth	Temp.*Lat.	Depth*Den./LPUE
Mean	0.00371	-	-	-	-	-	-	-
Median	0.00199	-	-	-	-	-	-	-
25^{th} Pct.	0.00756	-	-	-	-	-	-	-
75^{th} Pct.	0.00166	-	-	-	-	-	-	-
Range	0.00258	0.0415	-	0.0410	0.0375	-	-	0.0232
Interquartile Range	4.06e-7	-	-	0.0174	-	-	-	0.0136
Minimum	-	-	-	-	-	-	-	-
Maximum	3.83e-5	0.0247	0.023	0.0431	-	0.00941	-	0.022
Skewness	1.40e-7	-	-	-	-	-	-	-
Kurtosis	-	0.00360	0.00582	-	-	-	0.00394	-
Density	0.02960	-	-	N/A	-	-	-	N/A

Table 3.3 *P values from Type III SS ANOVA conducted on ocean quahog size variables as dependent variables and environmental variables and interaction terms as independent variables. Only significant (p < 0.05) results are shown, non-significance is denoted by a dash (-).*

Size Variables	Depth (m)	Temperature (°C)	Latitude (°)	Density/ LPUE (clams/m²)	Dredge Type	Temp.*Depth	Temp.*Lat.	Depth*Den./LPUE
Mean	-	0.0253	0.0126	2.14e-09	-	-	0.0247	-
Median	-	0.00108	0.00226	-	-	-	0.000782	-
25th Pct.	-	0.00127	0.00069	-	-	-	0.00137	-
75th Pct.	-	-	-	1.78e-7	-	-	-	-
Range	7.08e-8	7.17e-7	3.48e-5	-	-	2.64e-8	2.53e-6	-
Interquartile Range	-	0.0131	0.0204	-	0.0182	-	0.0143	-
Minimum	-	5.60e-5	5.59e-5	-	-	-	7.00e-5	-
Maximum	1.47e-5	0.0104	-	-	-	1.76e-5	0.0197	-
Skewness	-	-	-	-	-	-	-	-
Kurtosis	-	-	-	-	-	-	-	-
Density	0.00196	-	-	N/A	-	0.0141	-	N/A

Table 3.4 *Significant factors from Atlantic surfclam principal component analysis on environmental variables and related variables on each axis. Factor load scores for environmental variables on each axis are included in parenthesis.*

Factors (with Eigenvalues)	Variables on Axis
PC1 (2.2625)	Density/LPUE (1.7122)
PC2 (1.7473)	Temperature (1.5486), Depth (-1.2648)
PC3 (0.7636)	Latitude (-1.3446)

Table 3.5 *Significant factors from Atlantic surfclam principal component analysis on size variables and related variables on each axis. Factor load scores for size variables on each axis are included in parenthesis.*

Factors (with Eigenvalues)	Variables on Axis
PC1 (5.9686)	Mean (-1.6582), Median (-1.664), 25th Percentile (-1.5927), 75th Percentile (-1.6961), Skewness (1.2114)
PC2 (2.0410)	Range (-1.0959), Interquartile Range (-1.1225), Minimum (1.6219), Maximum (-1.5955)
PC3 (1.1912)	Kurtosis (1.3822)

Table 3.6 *Significant factors from ocean quahog principal component analysis on environmental variables and related variables on each axis. Factor load scores for environmental variables on each axis are included in parenthesis.*

Factors (with Eigenvalues)	Variables on Axis
PC1 (3.1243)	Density/LPUE (1.876), Depth (1.842), Temperature (-1.390)
PC2 (1.0361)	Latitude (-1.6304)

Table 3.7 *Significant factors from Atlantic surfclam principal component analysis on size variables and related variables on each axis. Factor load scores for size variables on each axis are included in parenthesis.*

Factors (with Eigenvalues)	Variables on Axis
PC1 (5.0838)	Mean (-1.7445), Median (-1.7074), 25th Percentile (-1.7194), 75th Percentile (-1.6114), Skewness (1.0529)
PC2 (2.5729)	Range (1.6646), Interquartile Range (1.1045), Minimum (-1.2646), Maximum (1.1561)
PC3 (1.3802)	Kurtosis (-1.4441)

Table 3.8 *Analysis of variance (ANOVA) results for Atlantic surfclam PCA factors. Factors of size variables (listed in Table 5) were used as dependent variables in the ANOVA, and factors of environmental variables (listed in Table 4) as independent variables. Pearson correlation coefficients between factors listed in parenthesis. P-values for significant environmental variables are noted in italics.*

PCA Factor for Size Variables	Significant PCA Factors – Environmental Variables (with Pearson's Correlation Coefficient and p-values)
Factor 1 (Mean, Median, 25%, 75%, Skewness)	PC1 (Density/LPUE; -0.67; p < 2.2e-16) + PC2 (Depth/Temperature; -0.54; p < 2.2e-16) + PC3 (Latitude; -0.18; p = 7.007e-4)
Factor 2 (Range, ItqRange, Min, Max)	PC3 (Latitude; 0.24; p = 0.02392)
Factor 3 (Kurtosis)	PC3 (Latitude; 0.41; p = 6.325e-5)

Table 3.9 *Analysis of variance (ANOVA) results for ocean quahog PCA factors. Factors of size variables (listed in Table 7) were used as dependent variables in the ANOVA, and factors of environmental variables (listed in Table 5) as independent variables. Pearson correlation coefficients between factors listed in parenthesis. P-values for significant environmental variables are noted in italics.*

PCA Factor for Size Variables	Significant PCA Factors – Environmental Variables (with Pearson's Correlation Coefficient and p-values)
Factor 1 (Mean, Median, 25%, 75%, Skewness)	PC1 (Density/LPUE, Depth, Temperature; 0.56; p = 1.285e-9)
Factor 2 (Range, ItqRange, Min, Max)	PC1 (Density/LPUE, Depth, Temperature; 0.15; p = 1.293e-3)
Factor 3 (Kurtosis)	PC2 (Latitude; -0.07; p = 0.01047)

3.7 Figures

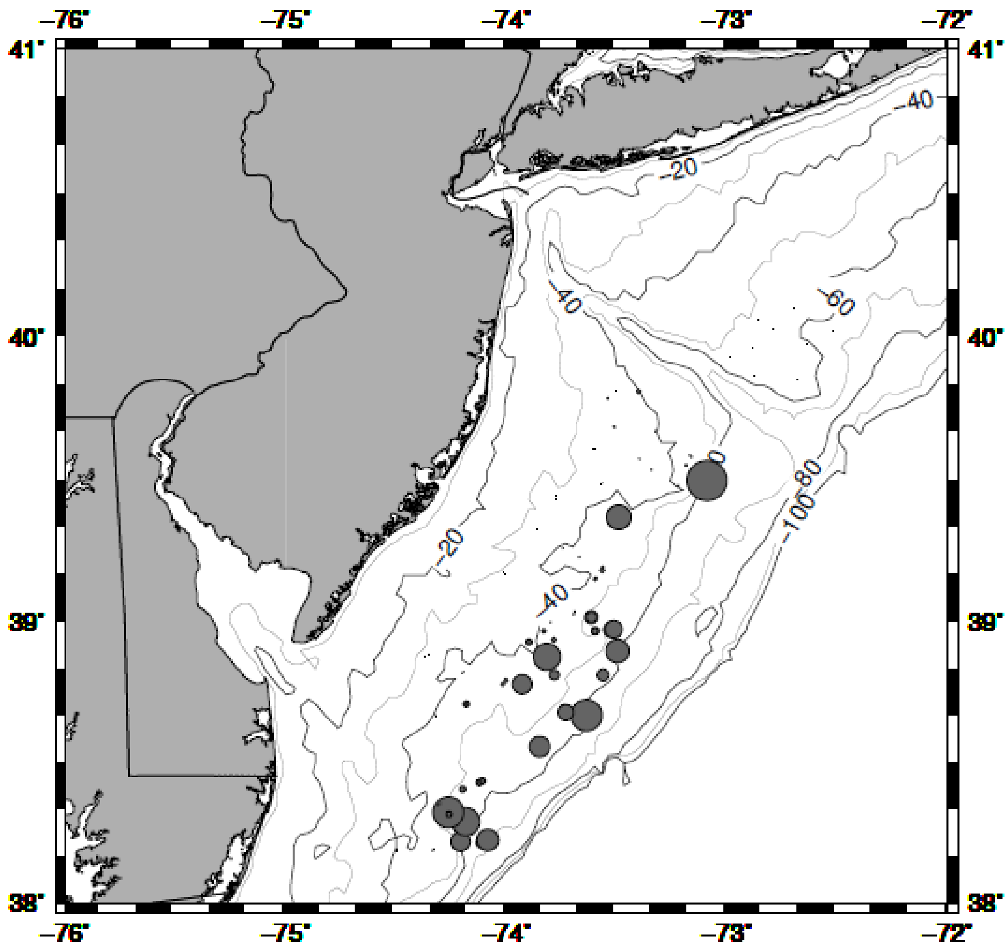

Figure 3.1 *Ocean quahog (Arctica islandica) density. Circle diameters are proportional to numbers per square meter.*

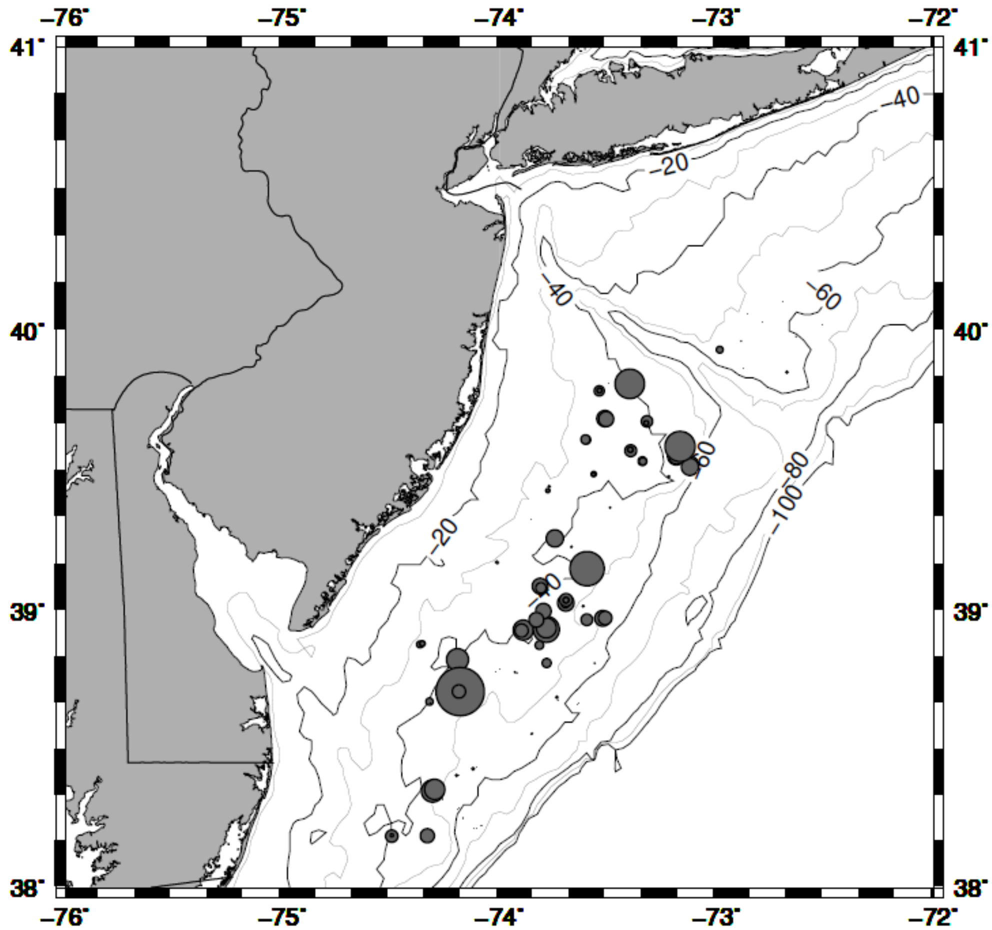

Figure 3.2 *Atlantic surfclam (Spisula solidissima) density. Circle diameters are proportional to numbers per square meter.*

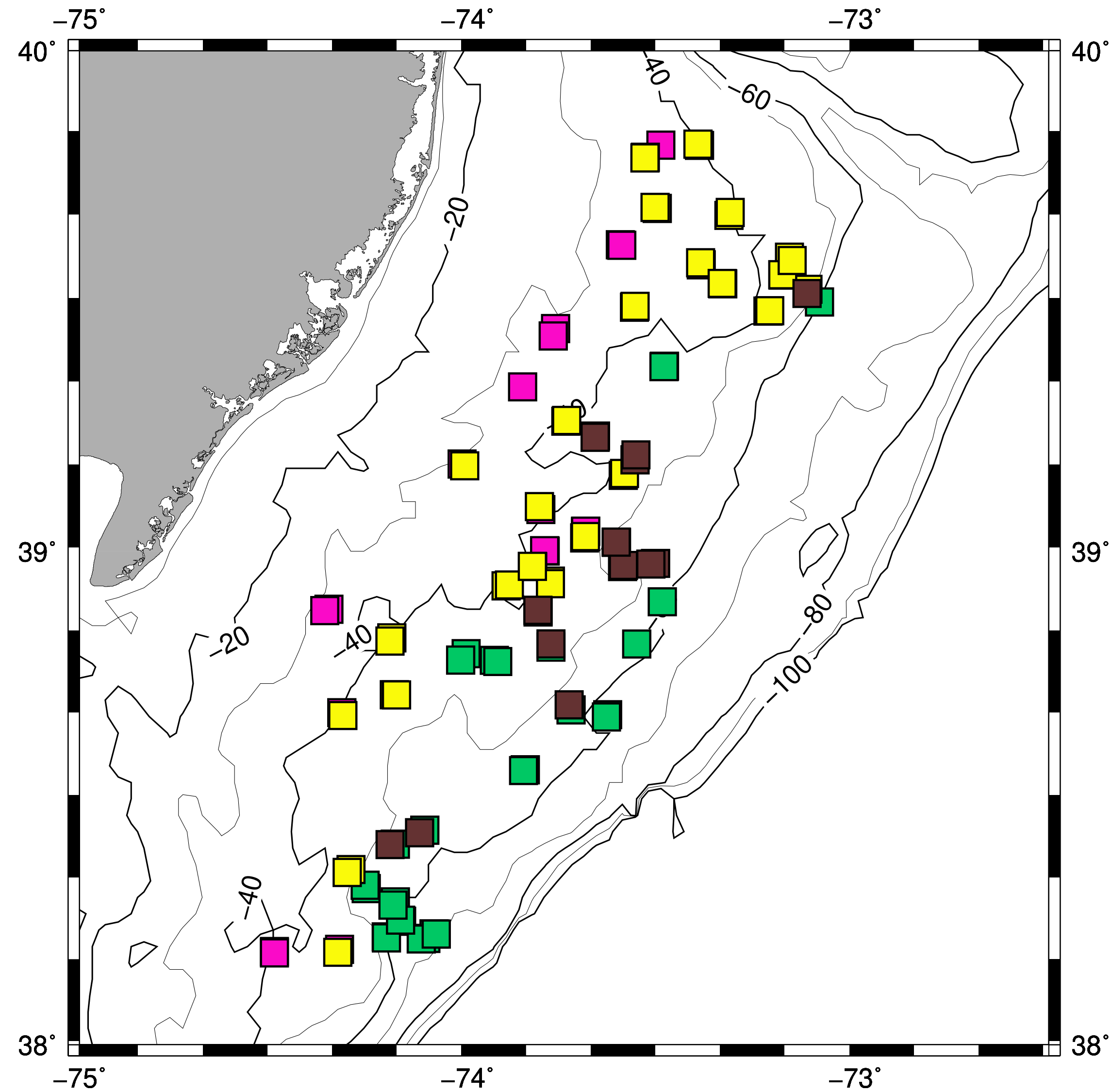

Figure 3.3 Pursuit survey locations sampled and catch characteristics. Dark pink boxes show locations where >24 of 25 clams were surfclams. Green boxes show locations where >24 of 25 clams were ocean quahogs. Yellow boxes show locations where at least 1 in 24 clams, but less than 12 in 24 were ocean quahogs. Brown boxes show locations where at least 1 in 24 clams, but less than 12 in 24 were surfclams.

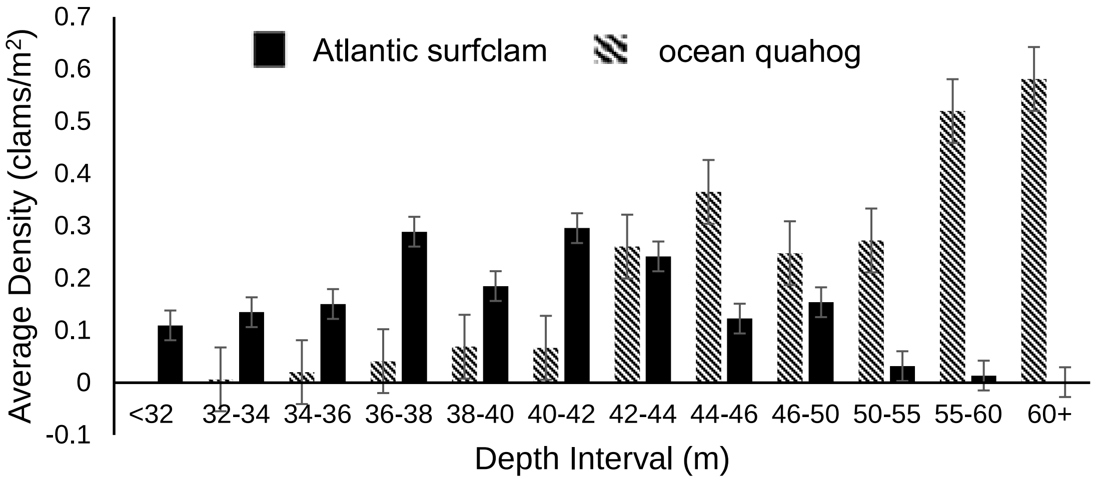

Figure 3.4 *Mean density by depth of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 2 m based on the depth of each tow, with the exception of the deepest tows that were placed in 5-m intervals as a result of few numbers of tows in these intervals.*

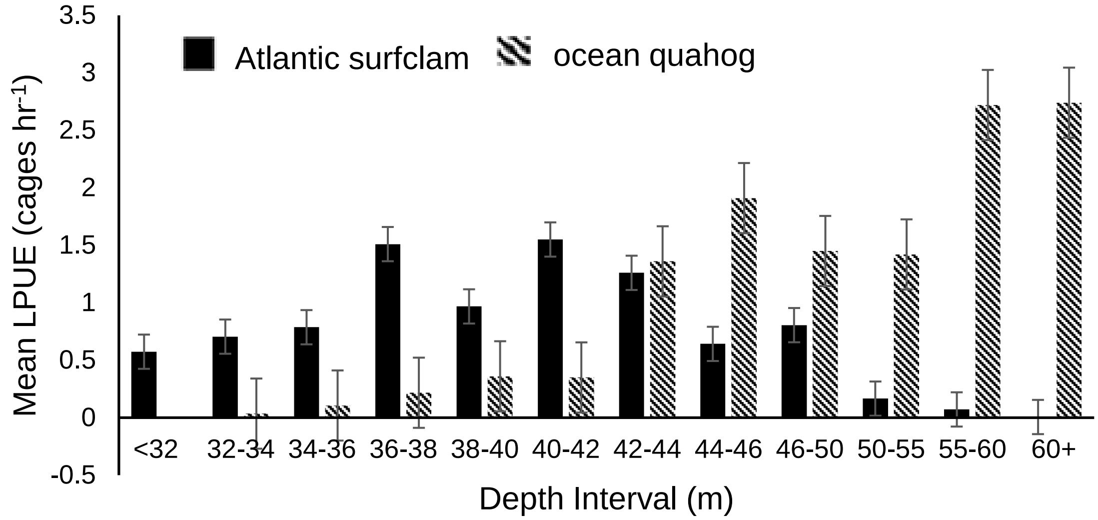

Figure 3.5 *Mean LPUE (cages hr-1, 1 cage = 32 surfclam bushels (1 bushel = 53.2 L)) of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 2 m based on the depth of each tow, with the exception of the deepest tows that were placed in 5-m intervals as a result of few numbers of tows in these intervals.*

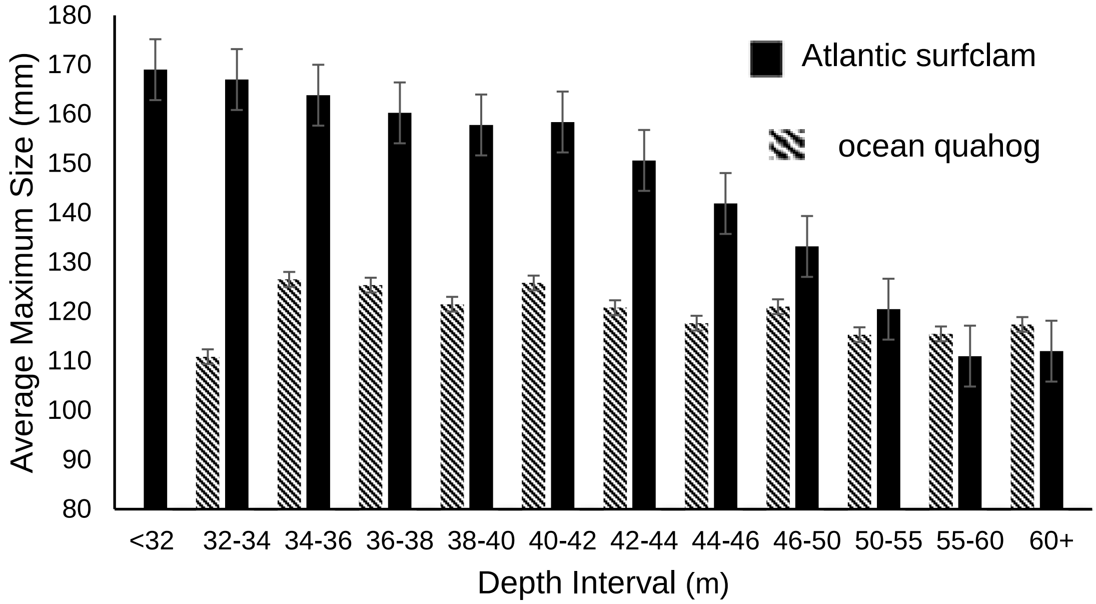

Figure 3.6 *Maximum size of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 2 m based on the depth of each tow, with the exception of the deepest tows that were placed in 5-m intervals as a result of few numbers of tows in these intervals.*

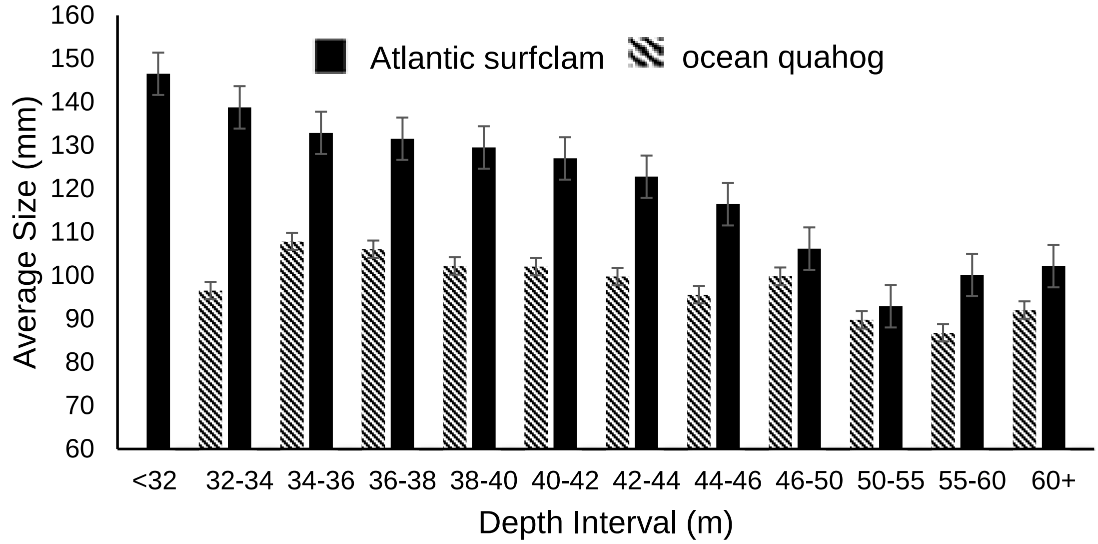

Figure 3.7 *Mean size by depth of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 2 m based on the depth of each tow, with the exception of the deepest tows that were placed in 5-m intervals as a result of few numbers of tows in these intervals.*

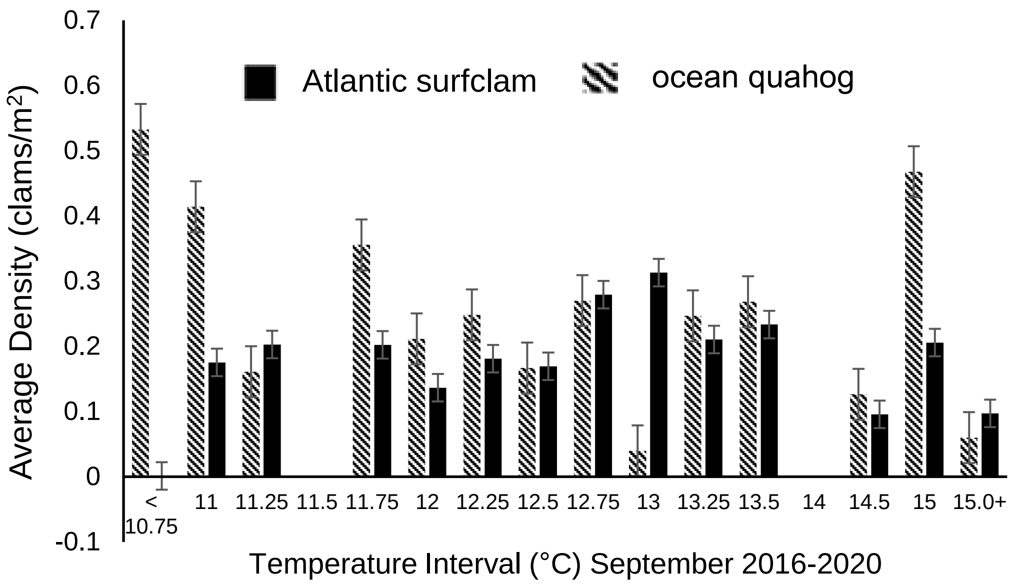

Figure 3.8 *Mean density by temperature of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 0.25°C based on the average September temperature from 2016 to 2020, with the exception of the highest temperatures which were placed in intervals of 0.5°C as a result of few numbers of tows in these intervals.*

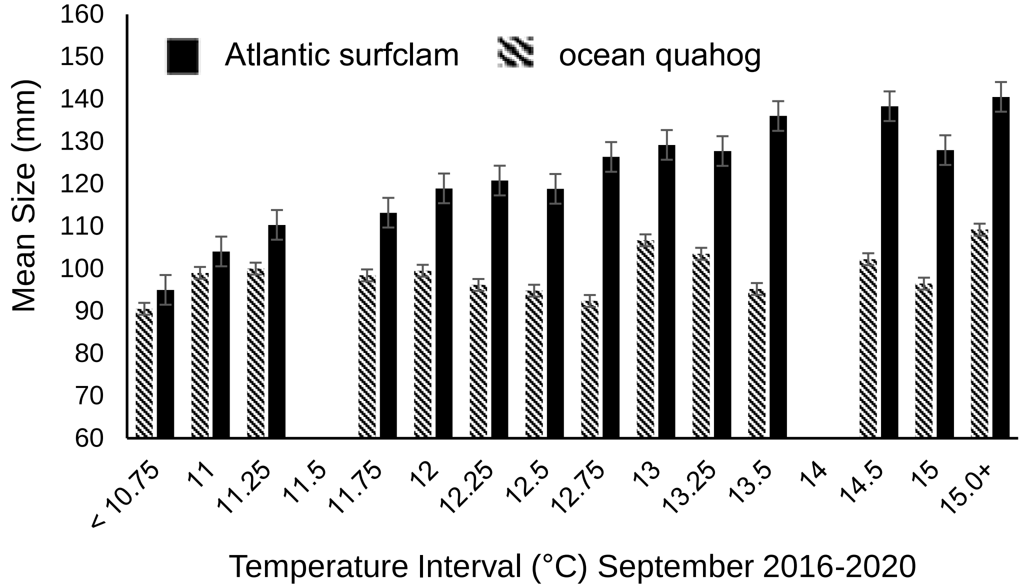

Figure 3.9 *Mean size by temperature of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 0.25°C based on the average September temperature from 2016 to 2020, with the exception of the highest temperatures which were placed in intervals of 0.5°C as a result of few numbers of tows in these intervals.*

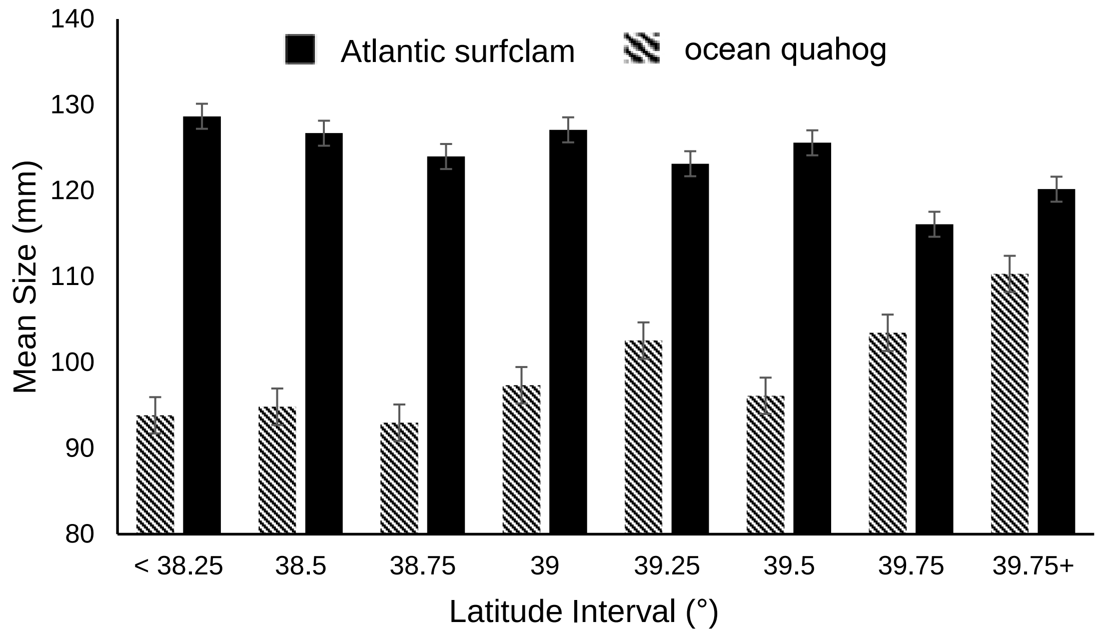

Figure 3.10 *Mean size by latitude of Atlantic surfclams and ocean quahogs across the survey domain. Survey stations were grouped into intervals of 0.25° latitude.*

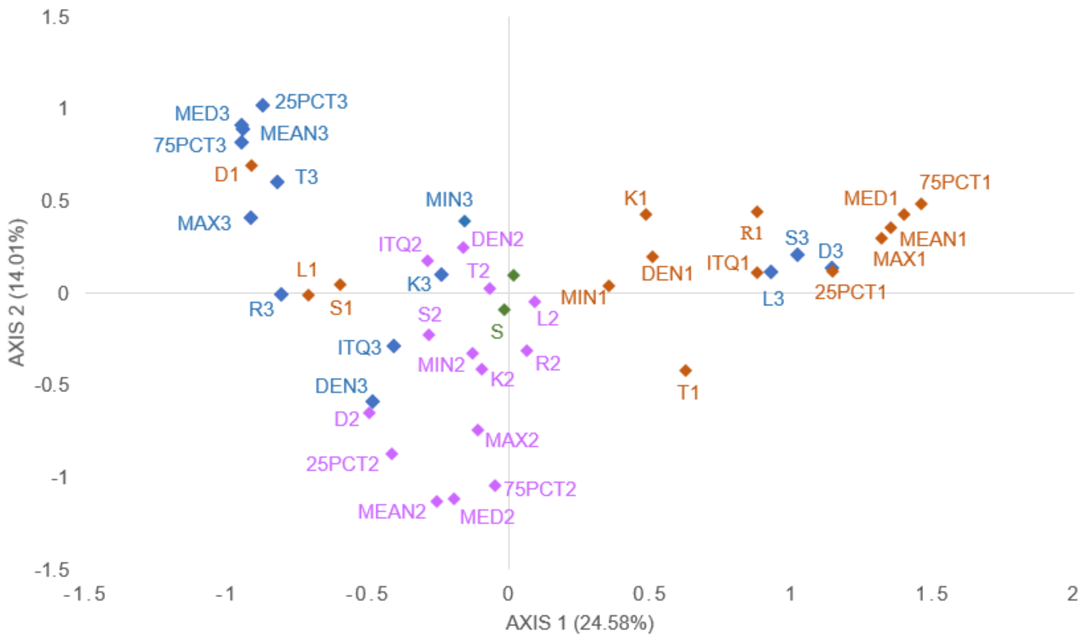

Figure 3.11 *Correspondence analysis of Atlantic surfclam size and environmental variables. Individual values for each variable were categorized into thirds and designated 1 (orange), 2 (purple), or 3 (blue), with 1 being the smallest values (highest latitude) and 3 being the largest values (lowest latitude). Size variable abbreviations: MEAN = mean size, MED = median size, R = range, ITQ = interquartile range, 25PCT = 25th percentile, 75PCT = 75th percentile, MIN = minimum size, MAX = maximum size, S = skewness, K = kurtosis. Environmental variable abbreviations: DEN = density, D = depth, T = temperature, L = latitude. Dredge types (P,S) in green are included as supplementary variables and not used to set up the axes.*

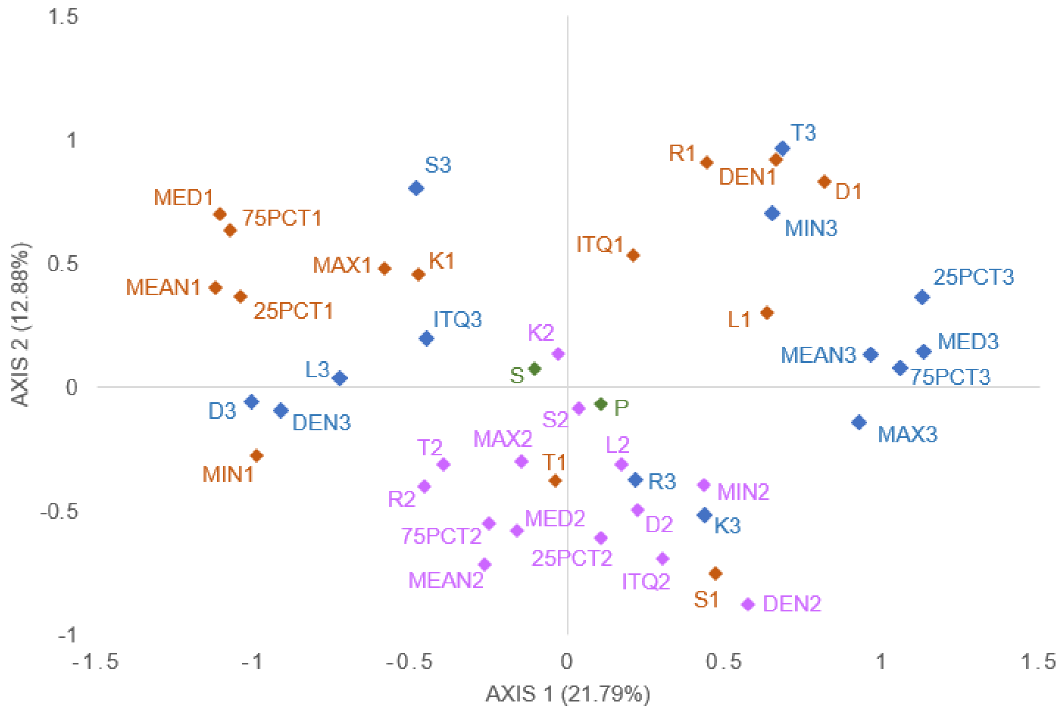

Figure 3.12 *Correspondence analysis of ocean quahog size and environmental variables. Individual values for each variable were categorized into thirds and designated 1 (orange), 2 (purple), or 3 (blue), with 1 being the smallest values (highest latitude) and 3 being the largest values (lowest latitude). Size variable abbreviations: MEAN = mean size, MED = median size, R = range, ITQ = interquartile range, 25PCT = 25th percentile, 75PCT = 75th percentile, MIN = minimum size, MAX = maximum size, S = skewness, K = kurtosis. Environmental variable abbreviations: DEN = density, D = depth, T = temperature, L = latitude. Dredge types (P,S) in green are included as supplementary variables and not used to set up the axes.*

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CHAPTER IV CONCLUSIONS

4.1 Range Shifts and Wind Energy

Rising water temperatures along the northeastern continental shelf have resulted in an offshore range shift of the Atlantic Surfclam, *Spisula solidissima*, to waters still occupied by ocean quahogs (*Arctica islandica*). Fishers presently are prohibited from landing both Atlantic surfclams and ocean quahogs in the same catch, limiting fishing to locations where the target species can be sorted on deck. Wind energy development on and around the fishing grounds will further restrict the fishery. SEFES, a spatially-explicit model of the Atlantic surfclam fishery, has the ability to simulate the consequences of fishery displacement due to wind energy development in combination with fishery and stock dynamics related to species overlap with ocean quahogs. Five sets of simulations were run to determine the effect of varying degrees of species overlap due to Atlantic surfclam range shifts in conjunction with fishing constraints due to wind farm development. Simulations track changes in relative stock status, fishery performance, and the economic consequences to the fishery. Compared to business-as-usual, all scenarios with less restrictive fishing penalties due to species overlap exhibited higher raw catch numbers but also greater reductions in revenue and increases in cost after the implementation of wind farms. This analysis serves to demonstrate the response of this fishery to combined pressures from competing ocean uses and climate change and emphasizes the potential for economic disruption of fisheries as climate change interacts with the evolution of ocean management on the continental shelf.

4.2 Degree of Co-occurrence in the Ecotone

Warming of the Mid-Atlantic continental shelf has resulted in a range shift of the Atlantic surfclam, *Spisula solidissima*, north and offshore into waters still occupied by ocean quahogs (*Arctica islandica*). As a consequence, an ecotone now exists over much of the offshore range of the surfclam in which surfclams and ocean quahogs co-occur. Regulations prohibit fishers from landing both species in the same catch, limiting fishing to locations where the target species can be sorted on deck. Fishery access to the ecotone region is vital as CPUEs have declined over the core of the surfclam's range. An at-sea survey sampling 50+ stations in the overlap region was conducted in September 2021 with the purpose of mapping fishable concentrations of surfclams and ocean quahogs. Size frequency and density data of both species were assessed along with environmental parameters. Species overlap between surfclams and ocean quahogs was most prominent in the 40-55-m depth range, where mean surfclam length declined by 40 mm compared to shallower waters. Density of surfclams shifted within this depth from surfclam dominant in <40 m to ocean quahog dominant in >60 m. Atlantic surfclam length increased with increasing summer bottom water temperature while densities remained stable, indicative of proportionately more larger but fewer animals in warmer inshore waters. The importance of bottom water temperature in determining surfclam distribution is revealed by significant temperature effects on 8 of 11 surfclam size variables, and correspondence analysis positions larger clams alongside high temperatures and shallow depths and small clams at deeper depths and lower temperature. Ocean quahog size metrics and densities, on the other hand, remain relatively unresponsive to temperature and invading Atlantic surfclam populations and instead increase in size with higher latitude. Large ocean quahogs, in particular, exhibit a distinct correlation with high latitude but fail to do so with other environmental variables. The lack of response in ocean quahogs during the last decade to environmental variables may be due to their long lifespan in comparison to surfclams and their ability to avoid high fall temperatures through burrowing resulting in a much slower movement of the species' range. This analysis emphasizes the potential for economic disruption of fisheries as climate change pushes surfclams further into the range of the ocean quahog and highlights the need for regulatory changes to allow mixed catches and landings. The study also emphasizes the importance of the relative rates of transgression and regression of range boundaries by abutting faunas in determining the degree of influence of the ecotone between them on the benthic community structure of the continental shelf.

APPENDIX A – FISHERY AND ECONOMIC PERFORMANCE METRICS

Table A.1 *Fishery performance metrics for each of the 25 simulations: LPUE (cages per hour fishing), average time at sea (hours per trip), average time fishing (hours per trip), and total trips (per year).*

	Q000	Q300	Q400	Q500	Q600
Average LPUE	1.72	1.49	1.44	1.401	0.69
Average time at sea	39.70	42.24	42.68	42.83	41.15
Average time fishing	23.87	25.43	25.64	25.66	20.72
Total trips	2091.67	1784.34	1740.54	1727.85	2601.97
	Q01T	Q31T	Q41T	Q51T	Q61T
Average LPUE	1.74	1.51	1.45	1.42	0.69
Average time at sea	40.00	42.78	43.33	43.44	41.47
Average time fishing	23.88	25.42	25.71	25.72	20.78
Total trips	2048.50	1714.09	1675.71	1661.05	2560.40
	Q01N	Q31N	Q41N	Q51N	Q62N
Average LPUE	1.76	1.52	1.47	1.44	0.71
Average time at sea	44.83	45.84	45.99	46.02	50.61
Average time fishing	23.72	25.14	25.33	25.33	20.84
Total trips	1941.71	1671.94	1636.99	1620.55	2252.79
	Q02T	Q32T	Q42T	Q52T	Q62T
Average LPUE	1.65	1.48	1.45	1.44	0.75
Average time at sea	41.49	44.22	44.46	44.52	41.42
Average time fishing	24.51	25.79	25.94	25.88	18.72
Total trips	1827.89	1612.75	1576.85	1565.78	2526.03
	Q02N	Q32N	Q42N	Q52N	Q62N
Average LPUE	1.67	1.49	1.47	1.46	0.76
Average time at sea	46.59	47.21	47.19	47.18	54.000.69
Average time fishing	24.24	25.51	25.53	25.53	17.86
Total trips	1740.67	1558.51	1531.23	1523.84	2107.74

Table A.2 *Economic performance metrics for each of the 25 simulations: total revenues (US$), total costs (US$), average total costs (US$/cage), and average fuel costs (US$/cage).*

	Q000	Q300	Q400	Q500	Q600
Total revenues (fleet)	3.93e7	3.10e7	2.59e7	2.86e7	1.50e7
Total costs (fleet)	4.38e7	3.73e7	3.62e7	3.56e7	3.54e7
Average total costs (fleet)	511.03	552.34	563.50	571.54	3.66e5
Average fuel costs (fleet)	161.37	186.02	192.51	197.16	1.98e5
	Q01T	Q31T	Q41T	Q51T	Q61T
Total revenues (fleet)	3.89e7	3.02e7	2.88e7	2.79e7	1.47e7
Total costs (fleet)	4.33e7	3.63e7	3.53e7	3.47e7	3.49e7
Average total costs (fleet)	509.79	552.90	564.19	572.02	4.08e5
Average fuel costs (fleet)	160.67	186.08	192.78	197.16	2.23e5
	Q01N	Q31N	Q41N	Q51N	Q61N
Total revenues (fleet)	3.72e7	2.93e7	2.80e7	2.71e7	1.43e7
Total costs (fleet)	4.26e7	3.60e7	3.50e7	3.43e7	3.48e7
Average total costs (fleet)	524.94	564.73	574.83	582.86	8.85e5
Average fuel costs (fleet)	174.53	196.08	201.52	205.92	5.86e5
	Q02T	Q32T	Q42T	Q52T	Q62T
Total revenues (fleet)	3.38e7	2.82e7	2.72e7	2.68e7	1.44e7
Total costs (fleet)	3.90e7	3.46e7	3.37e7	3.34e7	3.78e7
Average total costs (fleet)	529.10	562.84	569.39	572.68	6.97e5
Average fuel costs (fleet)	171.84	191.92	195.34	197.03	3.80e5
	Q02N	Q32N	Q42N	Q52N	Q62N
Total revenues (fleet)	3.23e7	2.72e7	2.64e7	2.61e7	1.40e7
Total costs (fleet)	3.83e7	3.40e7	3.33e7	3.30e7	3.38e7
Average total costs (fleet)	546.09	574.10	579.18	582.42	1.12e6
Average fuel costs (fleet)	186.88	201.07	203.42	205.25	7.34e5

Table A.3 *Percent change in fishing activity (rounded to the nearest hundredth) for each ocean quahog penalty case relative to the scenario without the ocean quahog catch penalty (Q0).*

	Q300	Q400	Q500	Q600
Average LPUE	-13.31	-16.12	-17.99	-59.67
Average time at sea	6.46	7.57	7.93	3.69
Average time fishing	6.56	7.43	7.52	-13.18
Total trips	-14.69	-16.78	-17.41	24.39
	Q31T	Q41T	Q51T	Q61T
Average LPUE	-13.22	-16.30	-18.07	-59.74
Average time at sea	6.95	8.32	8.61	3.68
Average time fishing	6.48	7.67	7.70	-12.98
Total trips	-16.32	-18.19	-18.91	24.99
	Q31N	Q41N	Q51N	Q62N
Average LPUE	-13.84	-16.66	-18.41	-59.77
Average time at sea	2.26	2.58	2.65	12.90
Average time fishing	5.99	6.82	6.79	-12.11
Total trips	-13.89	-15.59	-16.54	16.02
	Q32T	Q42T	Q52T	Q62T
Average LPUE	-10.24	-11.92	-12.51	-54.53
Average time at sea	6.54	7.14	7.28	-0.18
Average time fishing	5.24	5.82	5.61	-23.61
Total trips	-11.76	-13.73	-14.33	38.19
	Q32N	Q42N	Q52N	Q62N
Average LPUE	-10.49	-11.63	-12.38	-54.39
Average time at sea	1.31	1.27	1.24	15.89
Average time fishing	5.22	5.28	5.28	-26.32
Total trips	-10.46	-12.03	-12.45	21.08

Table A.4 *Percent change in economic metrics (rounded to the nearest hundredth) for each of the SEFES simulations relative to the case with no ocean quahog catch penalty (Q0).*

	Q300	Q400	Q500	Q600
Total revenues (fleet)	-21.09	-24.96	-27.16	-61.77
Total costs (fleet)	-14.80	-17.32	-18.52	-19.18
Average total costs (fleet)	8.08	10.26	11.84	7.1e4
Average fuel costs (fleet)	15.27	19.29	22.17	1.2e5
	Q31T	Q41T	Q51T	Q61T
Total revenues (fleet)	-22.58	-26.23	-28.56	-62.36
Total costs (fleet)	-16.12	-18.42	-19.76	-19.42
Average total costs (fleet)	8.45	10.67	12.21	8.0e4
Average fuel costs (fleet)	15.81	19.98	22.70	1.4e5
	Q31N	Q41N	Q51N	Q61N
Total revenues (fleet)	-21.23	-24.88	-27.27	-61.72
Total costs (fleet)	-15.37	-17.82	-19.31	-18.20
Average total costs (fleet)	7.57	9.50	11.03	1.7e5
Average fuel costs (fleet)	12.34	15.45	17.98	3.4e5
	Q32T	Q42T	Q52T	Q62T
Total revenues (fleet)	-16.56	-19.56	-20.83	-57.54
Total costs (fleet)	-11.32	-13.48	-14.35	-13.36
Average total costs (fleet)	6.37	7.61	8.23	1.3e5
Average fuel costs (fleet)	11.68	13.67	14.65	2.2e5
	Q32N	Q42N	Q52N	Q62N
Total revenues (fleet)	-15.65	-18.18	-19.29	-56.79
Total costs (fleet)	-11.37	-13.25	-13.84	-11.87
Average total costs (fleet)	5.12	6.05	6.65	2.0e5
Average fuel costs (fleet)	7.59	8.85	9.77	3.9e5

Table A.5 *Percent change in fishing activity (rounded to the nearest hundredth) for each wind farm case relative to the scenario without wind farms (00).*

	Q51T	Q51N	Q52T	Q52N
Average LPUE	1.07	2.12	2.33	3.71
Average time at sea	1.43	7.44	3.95	10.15
Average time fishing	0.21	-1.30	0.86	-0.52
Total trips	-3.85	-6.19	-9.36	-11.79

	Q01T	Q01N	Q02T	Q02N
Average LPUE	1.17	2.64	-4.08	-2.93
Average time at sea	0.79	12.97	4.58	17.43
Average time fishing	0.04	-0.62	2.68	1.58
Total trips	-2.06	-7.17	-12.61	-16.78

	Q31T	Q31N	Q32T	Q32N
Average LPUE	1.27	2.01	-0.68	0.22
Average time at sea	1.25	8.51	4.66	11.75
Average time fishing	-0.03	-1.16	1.40	0.31
Total trips	-3.93	-6.23	-9.61	-12.65

	Q41T	Q41N	Q42T	Q42N
Average LPUE	0.96	1.98	0.71	2.27
Average time at sea	1.50	7.73	4.16	10.56
Average time fishing	0.26	-1.19	1.15	-0.44
Total trips	-3.72	-5.94	-9.40	-12.02

	Q61T	Q61N	Q62T	Q62N
Average LPUE	0.99	2.40	8.14	9.78
Average time at sea	0.78	23.00	0.67	31.24
Average time fishing	0.26	0.60	-9.64	-13.78
Total trips	-1.56	-13.42	-2.91	-18.99

Table A.6 *Percent change in economic metrics (rounded to the nearest hundredth) for each wind farm case.*

	Q51T	Q51N	Q52T	Q52N
Total revenues (fleet)	-2.63	-5.46	-6.43	-8.98
Total costs (fleet)	-2.55	-3.60	-6.27	-7.29
Average total costs (fleet)	0.08	1.98	0.20	1.90
Average fuel costs (fleet)	0.00	4.44	-0.06	4.05
	Q01T	Q01N	Q02T	Q02N
Total revenues (fleet)	-0.86	-5.31	-13.90	-17.85
Total costs (fleet)	-1.11	-2.74	-10.90	-12.28
Average total costs (fleet)	-0.24	2.72	3.53	6.86
Average fuel costs (fleet)	-0.43	8.15	6.48	15.80
	Q31T	Q31N	Q32T	Q32N
Total revenues (fleet)	-2.73	-5.48	-8.96	-12.18
Total costs (fleet)	-2.64	-3.38	-7.26	-8.75
Average total costs (fleet)	0.10	2.24	1.90	3.93
Average fuel costs (fleet)	0.03	5.40	3.17	8.09
	Q41T	Q41N	Q42T	Q42N
Total revenues (fleet)	-2.55	-5.22	-7.71	-10.43
Total costs (fleet)	-2.42	-3.32	-6.76	-7.96
Average total costs (fleet)	0.01	2.01	1.04	2.78
Average fuel costs (fleet)	0.14	4.67	1.46	5.66
	Q61T	Q61N	Q62T	Q62N
Total revenues (fleet)	-2.40	-5.19	-4.40	-7.17
Total costs (fleet)	-1.41	-1.55	-4.48	-4.35
Average total costs (fleet)	11.67	142.06	90.64	207.32
Average fuel costs (fleet)	12.55	195.57	91.77	270.27

Table A.7 *Average annual catch in millions of bushels for the last 50 years of each case.*

SEFES case	Catch
Q500	1.90
Q51T	1.80
Q51N	1.75
Q52T	1.70
Q52N	1.65
Q000	2.60
Q01T	2.60
Q01N	2.40
Q02T	2.15
Q02N	2.10
Q300	2.05
Q31T	2.00
Q31N	1.90
Q32T	1.80
Q32N	1.80
Q400	1.95
Q41T	1.90
Q41N	1.80
Q42T	1.75
Q42N	1.70
Q600	1.00
Q61T	1.00
Q61N	0.95
Q62T	1.00
Q62N	0.95

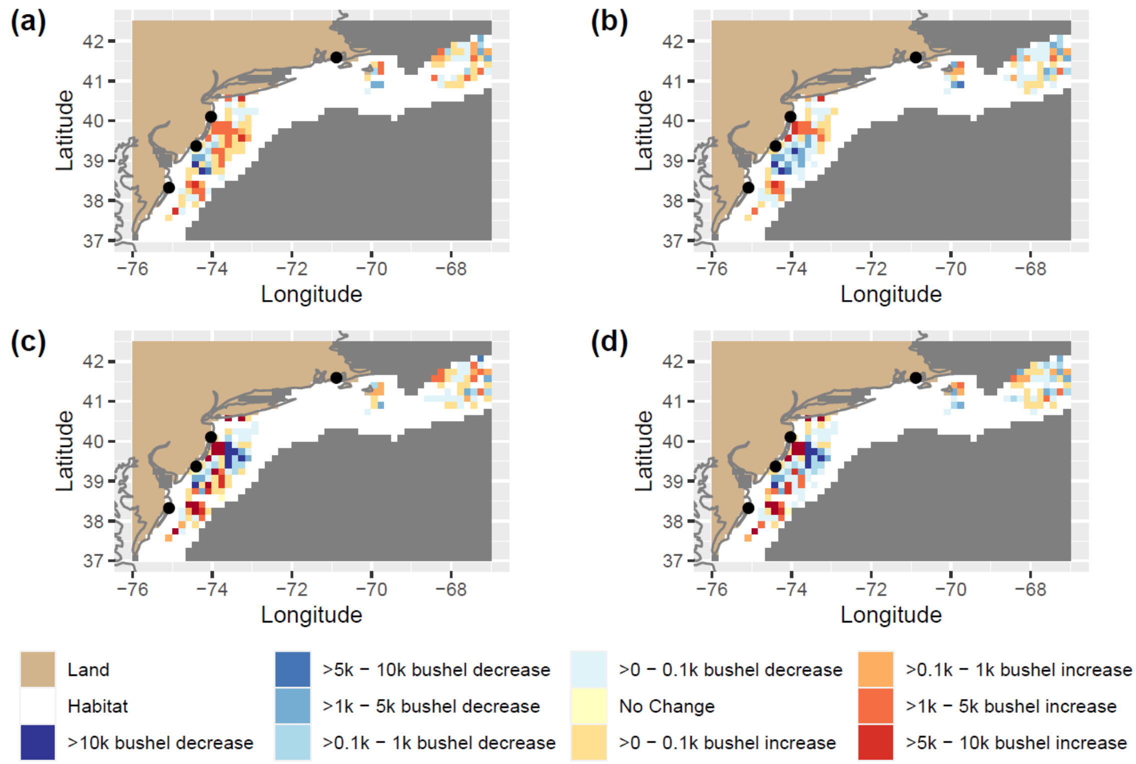

Figure A.1 *Spatial changes in catch, indicated by the change in catch per TMS per year, for each wind farm case as compared to the 30% ocean quahog penalty scenario without wind farms (Q300). (a) current leases with transit allowed, Q31T; (b) current leases with no transit, Q31N; (c) current and future leases with transit allowed, Q32T; (d) current and future leases with no transit, Q32N.*

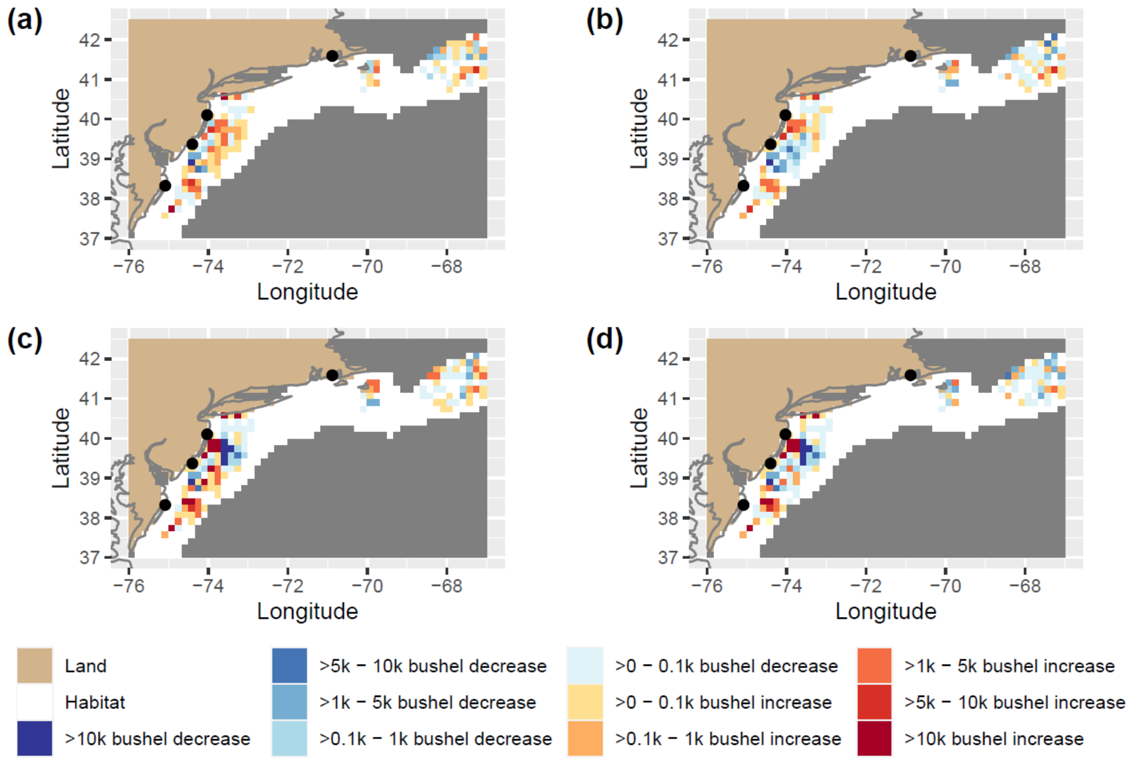

Figure A.2 *Spatial changes in catch, indicated by the change in catch per TMS per year, for each wind farm case as compared to the 40% ocean quahog penalty scenario without wind farms (Q400). (a) current leases with transit allowed, Q41T; (b) current leases with no transit, Q41N; (c) current and future leases with transit allowed, Q42T; (d) current and future leases with no transit, Q42N.*