Calibration Experiments for a Novel Clam Survey Dredge and Monitoring Carbonate Chemistry of Surfclam Habitat

Authors and Affiliations:
Daphne Munroe, Sarah Borsetti, Grace Saba
Rutgers, The State University of New Jersey

Tom Dameron
Surfside Seafood Products LLC

Daniel Hennen, Jason Morson
NOAA Northeast Fisheries Science Center

Prepared for:
New Jersey Department of Environmental Protection
Division of Science and Research

Project Managers:
Caitlin McGarigal (Division of Science and Research)
Colleen Brust (Marine Resources Administration)

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Executive Summary

The Atlantic surfclam (*Spisula solidissima*) fishery is an important commercial fishery in the U.S. Northeast region, and particularly so for the state of New Jersey. Annual landings in this fishery net approximately 22,400 tonnes (50 million lbs.) worth over USD 30 million. The fishery is conducted in the Middle Atlantic Bight (MAB), a marine region where seasonal temperature extremes are undergoing long-term changes at rates faster than other continental shelves. Additionally, the Atlantic surfclam fishery has been identified among the most exposed to offshore wind energy development impacts due to overlap of surfclam habitat and prime fishing grounds with wind energy areas (Scheld et al., 2022). Vulnerability of surfclam, and other fishery stocks in the region, to climate stressors must be evaluated so that stock changes over time can be attributed to climate, offshore wind development, or the combination of the two.

To address this, this project built a specialized scientific hydraulic dredge, based on plans provided by fishing industry collaborators, and conducted experiments to quantify the performance of this new experimental dredge. The dredge design and the small vessel used to tow it are intended to improve maneuverability and support post-construction survey efforts. The performance of the dredge was evaluated in three experiments: a paired-survey experiment that would allow direct comparison of data collected using the experimental dredge to that collected by the long-running federal survey; a depletion experiment that would directly measure capture efficiency; and a selectivity experiment to estimate the size-selectivity of the dredge. The data provided from these experiments was intended to support data integration with other survey platforms and allow absolute surfclam abundance estimates to be made. Whilst not designed as a "preconstruction" resource survey, the study design occupied stations in and around several lease areas and the data collected are contributing to preconstruction monitoring requirements. The dredge was also used to collect biological samples that were used to evaluate biological responses, including growth and shell strength, that were co-located with oceanographic observations of bottom water environmental conditions.

On the first survey sampling trip using the experimental dredge, it proved to effectively sample a broad size range of clams from the bottom while minimizing capture of additional shell and other debris. When compared to the federal survey platform, this experimental dredge demonstrated similar overall sampling efficiency; however, size selectivity differed among the two platforms, with the experimental dredge catching the smallest and largest size classes of surfclams more effectively than the federal survey platform, and the two catching similarly for middle sizes of clams. The efficacy of the experimental dredge as a survey tool has now been demonstrated by its use thus far in four surfclam surveys conducted as part of offshore wind fishery monitoring programs for leases (OCS-A 0498, OCS-A 0483, and OCS-A 0499).

Samples of surfclams collected in this program provided information about the population of surfclams off New Jersey, in and around offshore wind lease areas. Surfclams collected represented age classes from < 1 year old (collected in benthic grabs) through 31 years old. All age classes were consistently observed across surveyed locations, suggesting that recruitment of surfclams has been consistent in federal waters off New Jersey in recent decades. Density estimates of 0 to 0.6 adult surfclams per m^2 are consistent with populations of clams that range from below fishable density to densities that can support the fishery (>0.5 clams m^2; Powell et al., 2016; Powell et al., 2017). Based on biological clam data collected in this project, it appears that shell strength may not be the ideal parameter with which to determine stress in surfclams because shell strength is a physiological metric derived from integrated environmental conditions over relatively long periods of time. Other biological parameters such as body condition and transcriptomic responses may be better able to illuminate the response of surfclams to short-term stressful bottom conditions that may be impacted by seasonal or episodic warming or acidification and/or development of offshore wind.

By developing new surfclam survey tools and by addressing gaps in our understanding of the biological conditions of the surfclam fishery stock off New Jersey's coast, this project aligns with the vision of the NJ Research and Monitoring Initiative (RMI). The objectives and results of this study directly support offshore wind monitoring efforts by aiming to characterize the mechanisms underlying interactions among offshore wind construction and operations and key regional resources. Given the commercial and economic importance of the surfclam fishery to New Jersey, this project will benefit the state by supporting a better understanding of the benthic resources supporting the stock, and how that may or may not change with growth of offshore wind. Increased capacity for data comparison and data integration from multiple survey platforms will support our ability to investigate regional patterns in stock biology and status; such regional analyses will help us understand the dynamics of commercially important stocks as they respond to changing ocean conditions and growth of offshore wind.

Introduction and Motivation

This project advances the New Jersey Offshore Wind Research and Monitoring Initiative (NJ RMI) by developing and characterizing a new fishery monitoring tool that can be used to survey surfclam stocks and assess their possible response to offshore wind activities. By addressing key gaps in our understanding of the response of the surfclam fishery stock to stressors, this project aligns with NJ RMI's short-term highest-priority research areas, specifically 3 (Benthos) and 13 (Fisheries). Further, in accordance with the stated goal of the RMI, this study employed the best available scientific methods to support the State's mandate to protect and responsibly manage one of New Jersey's most valuable marine fisheries. The study was developed through a collaboration between Rutgers University, Surfside Seafood Products, NOAA's Northeast Fisheries Science Center, and the New Jersey Department of Environmental Protection (NJDEP) in a series of monthly interagency meetings, beginning in April of 2021, intended to identify research needs for the surfclam industry. Several RMI objectives are met with this scientifically rigorous, hypothesis-based, and scientifically defensible research. The results will be usable by surfclam fishery managers to inform actions for adaptive management to avoid, minimize, and/or mitigate impacts by providing a method to assess surfclam resources pre- and post-construction.

The Atlantic surfclam (*Spisula solidissima*) fishery is an important commercial fishery in the U.S. Northeast region, and particularly so for the state of New Jersey. Annual landings in this fishery net approximately 22,400 tonnes (50 million lbs.) worth over USD 30 million. The fishery is conducted in the Middle Atlantic Bight (MAB), a marine region where seasonal temperature extremes are undergoing long-term changes at rates faster than other continental shelves (Saba et al., 2016; Friedland et al., 202; Amaya et al., 2023) The MAB region is characterized by a strong seasonal thermocline that overlies and stabilizes a cold pool of water on the bottom (Horwitz et al., 2023). This cold bottom water sustains boreal fauna over a range that extends farther south than would be anticipated just by latitude (Borsetti et al., 2018; Narváez et al., 2015).

The Atlantic surfclam fishery has been identified among the marine fisheries most vulnerable to offshore wind energy development impacts. The fishery catches relatively high volumes at small profit margins, making it highly vulnerable to small shifts in economic efficiency. In general, bivalve shellfisheries are expected to be some of the most impacted in fisheries due to the incompatibility of fishing around farm cables, scour protection, and turbine bases given the type of gear (bottom-dredge) and vessels used (Kirkpatrick et al., 2017). Although wind developers will not legally prevent access to their project areas, it is anticipated that wind farm infrastructure will prevent commercial clam fishing in the lease areas and prevent the federal survey vessel (the F.V. E.S.S. Pursuit) from accessing the wind lease areas once construction has begun (Methratta et al., 2020). A recent analysis found that fishery displacement arising from offshore wind energy development would reduce revenues in the Atlantic surfclam fishery by 3-15%, with revenue losses as large as 25% for certain New Jersey ports (Munroe et al., 2022; Scheld et al., 2022). Development of offshore wind energy is anticipated to affect stock assessment surveys, as survey vessels will be unable to access stations within wind lease areas, increasing uncertainty in estimation of biological reference points and complicating management decisions (Borsetti et al., 2023; Methratta et al., 2023). These vulnerabilities underscore the need to include a survey of surfclams in any fishery monitoring plan, at a minimum, for leases where overlap exists between surfclam habitat, fishing activity, and wind development.

Surveys of benthic fauna in the Mid-Atlantic continental shelf using grab samplers or box cores, which are typically used for macrobenthic sampling, are insufficient for measuring impacts of offshore wind development on commercial clam stocks. A survey tool that samples over a much larger area than a core is needed to accurately estimate the biomass, abundance, and size structure of the very large-bodied clams that make up a substantive and commercially important component of the benthic biomass on the Mid-Atlantic shelf. Munroe and colleagues (2023) provide an outline of best practices for surveys of high biomass benthic fauna, recommending the use of a commercial hydraulic dredge as most effective. Such a tool, once fully calibrated, would be critical for supporting clam resource surveys before, during, and after offshore wind construction.

A hydraulic dredge has been designed[*] through an industry-science collaborative process that could allow surveying within and around lease areas. The dredge is designed to catch a wider size range of the clam population than a standard commercial dredge and is intended to be fished using a moderately sized vessel that can more easily maneuver safely within a wind farm lease area. For this dredge to be used to survey clams within wind lease areas, it is imperative to assess the capture efficiency and size selectivity, and to calibrate the dredge against the federal survey platform. This information would ensure that the data collected with this tool could be integrated with existing, long-term data collected by the federal survey.

To evaluate changes over time in surfclam and other fishery stocks in the region, vulnerability of these stocks to climate stressors must be evaluated so that stock changes over time can be attributed to climate, offshore wind development, or the combination of the two. The habitats occupied by surfclams and the fishery are subject to ocean acidification and warming water conditions. Recent research has demonstrated that surfclams are susceptible to both of these environmental stressors (Narváez et al., 2015; Pousse et al., 2020). During the summer, bottom water in the coastal ocean offshore of New Jersey experiences reduced pH and aragonite saturation (Wright-Fairbanks et al., 2020) and upwelling events further reduce pH and aragonite saturation in this area (Poach et al., 2019). Further, NJDEP published the 2020 New Jersey Scientific Report on Climate Change, which states, “New Jersey is at increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests, with southern New Jersey counties ranking second in the United States in economic dependence on shelled molluscs.” To better understand the response of surfclams to realistic climate stressors, carbonate

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[*] Dredge plans can be found at: https://sites.rutgers.edu/munroe-lab/resources/

chemistry of bottom water habitats supporting surfclams need to be better characterized, particularly where wind leases may interact with oceanography to alter these conditions. One of the largest gaps in ocean acidification research, identified by federal and several state agencies and committees, is co-located biological response monitoring (Goldsmith et al., 2019).

Co-located measurements of carbonate chemistry and shellfish biology are important for understanding how changing ocean conditions may affect commercial stocks like surfclams. Most of what we know about organismal response to ocean acidification derives from single-species laboratory studies and often do not capture realistic, natural conditions or variability. Therefore, simultaneous measurements of surfclam biological response indicators (e.g., abundance, size, shell strength, condition index) must be performed under naturally varying conditions (e.g., Steeves et al., 2024) or be co-located with carbonate chemistry observations in the field to observe and predict biological responses.

In this project, a specialized experimental hydraulic dredge was built based on plans provided by fishing industry collaborators, and experiments were performed to quantify the performance of the experimental dredge. The dredge was also used to collect biological samples that were used to evaluate biological responses including growth and shell strength that were co-located with oceanographic observations of bottom water environmental conditions.

Project Design and Methods

This project consisted of two related efforts. The first, was to construct, evaluate, and correlate the performance of an experimental surfclam survey dredge with the current federal survey dredge platform. The second was to collect co-located biological and environmental data to inform our mechanistic understanding of the response of surfclams to realistic ocean acidification conditions.

Dredge Construction and Calibration

In the spring of 2022, Dorchester Shipyard (Dorchester, NJ), a local firm with experience and expertise building and installing hydraulic dredges was engaged for the construction, delivery and installation of the experimental surfclam survey dredge, also known as the 'Rutgers-RMI Dredge'. The dredge was originally designed through an industry-science collaborative process[†]. It was constructed of A-36 steel with 10" (25.4 cm) AR500 hard plate runners and was similar to commercial fishery dredges with the exception of the bar spacing and an adjustable floor. The bar spacing on the top, sides, and back of the dredge were kept at ¾" (typical spacing for a commercial dredge), while the bottom of the dredge can be reduced to ¾", the typical spacing for a commercial dredge being 1 ¾", while the bottom of the dredge can be adjusted to a ¾" minimum and 1 ¾" maximum spacing by way of thirty (30) adjustable hinges and four (4) control hinges. The dredge was fitted with a 10" schedule 80 pipe manifold and accepts a 10" clam jetting hose to minimize friction loss through the clam hose. A series of 30 evenly spaced ¾" schedule 40 pipe nipple spray nozzles were set at 51 degrees and 39 ½" from the 4" knife blade on a 39 1/8" knife carrier. The manifold is on a fixed mount base (non-adjustable) for maximum consistency over the life of the dredge. The dredge door is fitted with automatic tripping and self-closing mechanisms that were fitted to the survey vessel (*F.V. Joey D*) for safe operation.

The performance of the experimental dredge was evaluated in three experiments: a paired-survey experiment that would allow direct comparison of data collected using the experimental dredge to that collected by the long-running federal survey; a depletion experiment that would directly measure capture efficiency; and a selectivity experiment to estimate the size-selectivity of the experimental dredge. The data provided from these experiments was intended to support integration of the data collected with this experimental dredge with other survey platforms and allow absolute surfclam abundance estimates to be made.

[†] The design plans can be viewed at: https://sites.rutgers.edu/munroe-lab/resources/

Paired Surveys

Surveys for surfclams were conducted between August 18-22, 2022, on two fishery survey vessels, the *F.V. E.S.S. Pursuit (carrying the federal survey dredge)* and the *F.V. Joey D (carrying the experimental survey dredge)*. At 44 m (145.5 ft.) long, the *F.V. E.S.S. Pursuit* is a larger vessel than the 24 m (78.8 ft.) long *F.V. Joey D*. The *F.V. E.S.S. Pursuit* can carry two 3.81 m wide dredges (only one was used in this survey), with a bar spacing on the dredge that is 3.5 cm (1.375 in.). In contrast, the *F.V. Joey D* carries a single 2.54 m (8.3 ft.) wide dredge with narrower than normal bar spacing at 1.9 cm (0.75 in.). The *F.V. E.S.S. Pursuit* has a catch efficiency, established using previous depletion experiments, of 0.67 (NEFSC, 2017).

Each vessel collected surfclam samples using standardized hydraulic dredge tows at the same 39 survey stations within 48 hours of one another, off the coast of New Jersey in water depths ranging from 13 to 48 m (43 to 157 ft.) (Figure 1). The stations used were a subset of federal surfclam survey stations, which were selected at random within federal surfclam strata, as part of the federal fishery survey process (NEFSC,2017). At each station, each vessel conducted a 5-minute tow at approximately 2.5 to 3 knots following standard protocols used in the NOAA federal surfclam survey (NEFSC, 2017; Munroe et al., 2023). For all tows, a tilt sensor (Star Oddi DST tilt) was fixed to each dredge and recorded pitch, roll, and yaw of the dredge at a frequency of 0.5 Hertz, and a GPS was used to record vessel speed and location during each tow. These recorded data were used to evaluate the bottom area contacted during each tow to estimate swept area per tow. A pressure sensor (MadgeTech PR1000) attached to the manifold on each vessel recorded water pressure within the dredge manifold to ensure water pressure remained consistent for each tow.

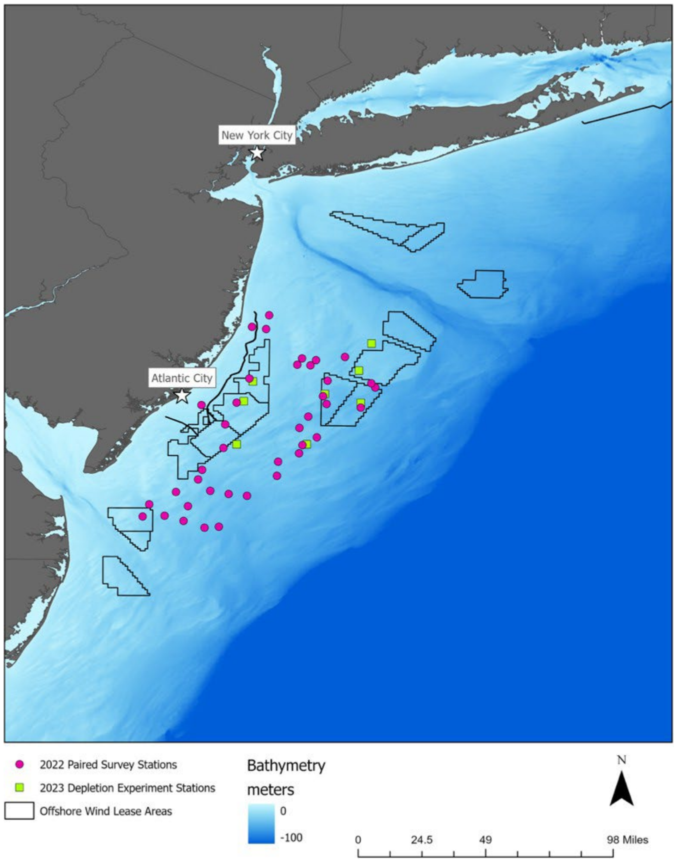

Figure 1: Locations of the survey stations occupied in 2022 by both vessels (pink circles) and the 2023 depletion stations (green squares). Offshore wind lease areas outlined with black polygons for reference.

Catch from each tow was sorted by species on deck and the total volume (measured in 42L bushel baskets) of surfclams caught was measured. A randomly selected subsample (1 bushel) of the surfclam catch was counted (number of individual surfclams per bushel), and the shell lengths of all surfclams in the subsample were measured to the nearest 0.1 mm using a digital length board. The subsample was extrapolated to total catch per tow by multiplying the subsample by the total volume caught. The total count of surfclams and length frequencies were used to estimate the wet meat weight of the surfclams in each tow using an established allometric weight-at-length relationship for surfclams (Marzec et al., 2010). Total catch and total biomass were then corrected to the area sampled in each tow (swept area) to standardize among the two different dredge sizes. The swept-area catch (number of surfclams per area sampled) and the swept-area biomass (wet weight in grams per area sampled) from the two vessels were compared pairwise across all 39 stations using a paired t-test to evaluate the relative catchability between platforms. The length frequency caught across all 39 stations was compared between the two survey platforms using a Kolmogorov–Smirnov (K-S) test. The selectivity ratio (S) at length (L) of the *F.V. JoeyD* relative to that of the *F.V. E.S.S. Pursuit* was calculated as the ratio of the catch per unit effort (CPUE) at length of the two surveys following Kotowicki et al. (2017):

$$S_{L,JoeyD,Pursuit} = \frac{CPUE_{L,JoeyD}}{CPUE_{L,Pursuit}} \quad \text{(Eq. 1)}$$

Depletion Experiments

From August 15-18, 2023, eight locations were used to conduct eight separate depletion experiments (Figure 1) on board the *F.V. Joey D*. The locations of the experiments spanned a range of depths from 25 to 43 m (82 to 141 feet), bottom types, and surfclam abundances because capture efficiency of fishing gears is known to vary with these parameters (Wilberg et al., 2010; Delargy et al., 2023). At each depletion experiment location, a target area [50 m wide by 500 m long (164 ft. by 1,640 ft), that follows the local bathymetry to produce tows that are relatively level] was identified and mapped onto the vessel's chart plotter. The target area was used as a reference so that tows could be made repeatedly in one location until the location was deemed 'depleted' of surfclams. For each tow, the catch was sorted by species, the total volume of surfclams was measured and the number of surfclams in a one-bushel subsample was counted. For tows catching less than one bushel, all surfclams were counted. In each experiment, the first tow and every third tow after the first, shell lengths in a one-bushel subsample were measured. A GPS receiver (ArrowGold GNSS) was used to record location every 2 seconds at a resolution of <0.5 m (1.6 ft.); location information was passed to ArcGIS Pro after each tow and the Python package *arcpy* was used to evaluate tow overlap. Tow overlap was estimated by setting a buffer distance in ArcGIS of 1.25 m (4.1 ft.) on either side of each tow track to make a polygon the width of the dredge and the length of each tow, then summing the total areas of overlapping tows (polygon overlap) and dividing by the total area occupied by all tows combined.

Three conditions were monitored after each tow to determine whether the location had been 'depleted': the depletion of catch volume, the depletion of catch abundance (number of surfclams caught), and tow overlap. Depletion of the catch volume and abundance was evaluated (1) relative to the highest catch observed in the experiment and (2) using a depletion curve fit to the time series of the catch. When the catch (both volume and number caught) dropped below 20% of the highest catch observed, and the slope of the depletion curve dropped below 20% of the maximum slope, the catch was considered depleted. Additionally, the tows were considered sufficiently overlapped when 80% of all towed area was contacted by a minimum of two (possibly more) tows. When all three of these conditions were met, the experiment was considered complete.

The catch and tow track location data were used to estimate the experimental dredge capture efficiency for each experiment following Hennen et al. (2012). In this analysis, a sequential hit matrix for the area covered by each tow was used to estimate the amount of bottom contacted by the dredge repeatedly over the course of a given experiment. The matrix that was used for each experiment had a spatial resolution of 1.0 cm and encapsulated all tow locations. For each tow track, the number of locations in the hit matrix that are contacted by the dredge was evaluated and the number of times that a given point is contacted across all tows was calculated. A Patch-model (Rago et al., 2006) was then used to estimate surfclam density and dredge efficiency for each experiment. These depletion experiments provide data that can be used to directly estimate dredge efficiency (Rago et al., 2006; Hennen et al., 2012; Wilberg et al., 2013; Poussard et al., 2021).

Selectivity Experiment

On August 13, 2023, ten stations were sampled twice with the *F.V. Joey D*; one 5-minute tow made with the experimental dredge in open bar spacing [4.4 cm (1.7 in.) between bars] and a second 5-minute tow made with the dredge in closed bar spacing [2.0 cm (0.8 in.)]. The two tows were made next to one another, and not overlapping one another. Catch from each tow was sorted by species on deck and the total volume (in bushels) of surfclams caught was measured. A subsample (1 bushel) of the surfclam catch was counted (number of individual surfclams per bushel), and the shell lengths of all surfclams in the subsample were measured to the nearest 0.1 mm using a digital length board. Length distributions of the catch from the paired tows were compared to evaluate the selectivity of the experimental dredge in the two bar spacing configurations.

Surfclams and Bottom Water Conditions

On August 18-22, 2022, and August 12-13, 2023, Atlantic surfclam samples collected with standardized dredge tows (described above) and benthic grabs, and oceanographic measurements, including depth profiles of temperature, salinity, and carbonate chemistry (pH and pCO_2, the concentration of CO_2 in seawater), were made at 39 stations on the Mid-Atlantic shelf off the coast of New Jersey (Figure 1; 36 stations in 2022, 3 stations in 2023). These stations included habitats in and around wind lease areas and stations are described in the previous sections pertaining to dredge calibration.

In addition to hydraulic dredge sampling, a benthic sediment sampler (Peterson grab sampler) was used to collect samples of the seabed surface sediment and benthic macroinvertebrates at every station. The purpose of these samples was to characterize the young-of-the-year (juveniles < 1 year old) surfclams which are too small to be retained by the dredge. The grab was deployed over the side of the vessel and samples an area of bottom approximately $0.1m^2$ to a depth of 5 to 10 cm. Samples were brought on board and wet sieved through a 2.0 mm screen. All material retained on the sieve was bagged and returned to the laboratory for processing. From each sample, clams retained were identified to species, photographed using a microscope (10x magnification), and shell length measured.

Depth profiles of oceanographic and carbonate chemistry data were collected at each station with a Sea-Bird SBE 19plus v2 CTD (for measurements of salinity, temperature, and depth), a Sea-Bird SBE18 profiling pH sensor, and a flow-through Pro-Oceanus Systems, Inc. sensor. Water flow through the pCO_2 sensor was increased via an in-line Sea-Bird SBE 5P pump to reduce measurement equilibration time. The sensors were lowered, then held just above the bottom [in water depths < 23 m (75 ft.)] or below the determined thermocline [subsurface; in depths > 23 (75 ft.)] for 3-5 minutes[‡] to allow the pH and pCO_2 sensors sufficient time to equilibrate for accurate bottom or subsurface measurements. Mean bottom or subsurface pH, pCO_2, temperature, salinity, and pressure were calculated for each station by averaging the measurements made during the last one minute of static bottom or subsurface sampling. These mean values were used as inputs for the PyCO2SYS package in Python to resolve the full carbonate system including the calculation of subsurface or bottom water ΩArag and ΩCalcite at each station (Humphreys et al., 2021).

At three stations each year, discrete water samples were collected at multiple depths using a 5L Niskin bottle. The three stations in 2022 were the first, middle, and final stations on the cruise; the three stations in 2023 were in roughly the same water depth and spanned a latitudinal range along the central New Jersey coast. Collected water was transferred into borosilicate glass bottles, preserved with 0.02% final concentration of saturated mercuric chloride, and analyzed by Dr. Chris Hunt in a laboratory at the University of New Hampshire for pH, total alkalinity, and dissolved inorganic carbon. Samples were analyzed for pH spectrophotometrically at 25°C with purified meta-Cresol Purple dye (Clayton and Byrne 1993, Liu et al., 2011), total alkalinity via open cell Gran titration (Dickson et al., 2007, Chen et al., 2015) and dissolved inorganic carbon on an Apollo SciTech AS-C2 automated analyzer using the coulometric method (Cai and Wang, 1998; Dickson et al., 2007). Certified seawater reference materials from Dr. A. Dickson were used to check total alkalinity accuracy and to determine DIC concentration by preparing a calibration curve covering the range of DIC from 200 to 2000 $\mu mol\ kg^{-1}$ (Dickson et al., 2003). The measured carbonate chemistry from the bottles, along with temperature and salinity from the CTD profiler at water collection depths, were used as inputs for the PyCO2SYS package in Python to derive in situ pH and pCO_2. These bottle data were compared to sensor-based pH and pCO_2 data, to calculate offsets that determine the field accuracy of the pH and pCO_2 sensors (see data quality assurance plans in Appendix 2).

At each station, standardized tows were made using the experimental dredge to collect Atlantic surfclams (Munroe et al., 2023). Shells from a subsample (n~20 randomly selected) of the live animals collected at each station were shucked at sea and clean shells returned to the lab for processing. Shells were separated as left and right valve. The right valve was used for determining shell strength. If the right was damaged the left valve was used instead. Each shell was measured for shell length (longest axis) and thickness (at the growing edge across from the umbo), weight (dry weight of a single valve), and shell strength. Shell strength was estimated as the amount of force required to break the shell (LaBarbera and Merz, 1992; Roy et al., 1994) using an Instron 3400 Series Single Column

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[‡] The duration of sensor time at bottom was extended to 15 minutes for samples collected in 2023 because of sensor response time needs identified in 2022.

Table Model at a rate of 2.54 mm/min. The force (kiloNewtons, kN) applied in the middle of the shell at which the shell begins to break was assumed the force required to break the shell (Figure 2).

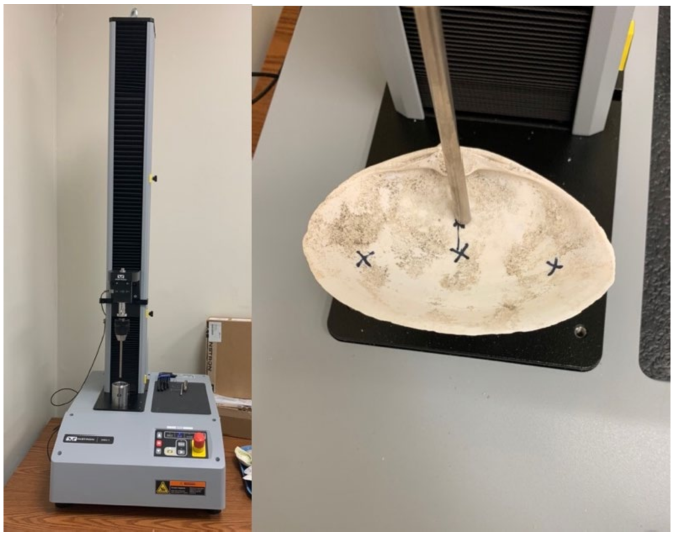


Figure 2: The Instron 3400 Series Single Column Table Model (left) used to measure shell strength (right). Markings on the shell are meaningless.

Other studies have shown that the resistance to breakage is related to factors such as shell weight and thickness (Vasconcelos et al., 2011). For all shells used in this study, shell strength was significantly correlated to shell weight (p<<<0.0001; d.f. = 527; F = 1722; Adj. R2 = 0.76, Figure 3); therefore, shell strength was standardized to shell weight (kN/g) for all subsequent analyses. For each station at which shells were collected, the average standardized shell strength was used to evaluate whether this biological metric was correlated with bottom water ΩArag, pH, pCO2, temperature, and depth using linear regression.

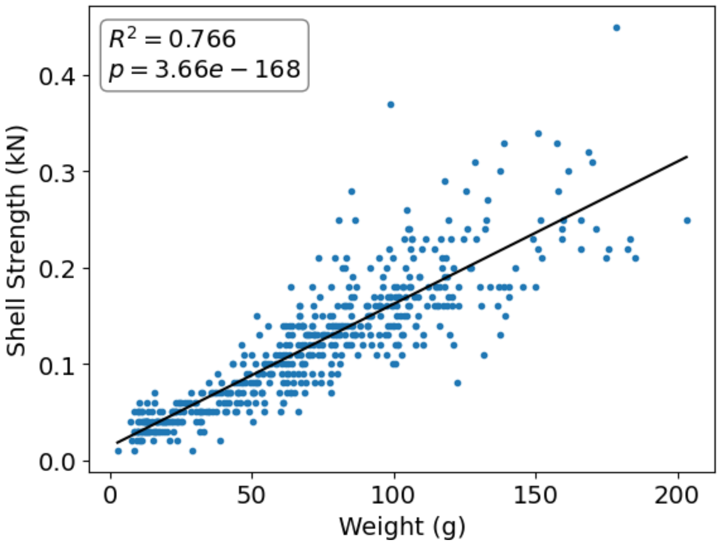


Figure 3: Shell strength (kN) and shell weight (g) are positively correlated. Thicker and heavier shells require more force to break.

The left valve of each animal was used for aging unless damage to the shell would prevent an accurate reading. A line was drawn across the longest portion of the chondrophore (Figure 4) and then extended across the entire valve to use as a guideline when sectioning the shell. Before sectioning the shell, each one was filled with modeling clay to add support and prevent breakage. Sectioned shells were polished on an EcoMet 30 Manual Grinder-Polisher to reveal growth lines (Figure 4). Shells were polished using grinding paper (200 grit followed by 400 grit) followed by diamond suspension polishing solutions. Emphasis was placed on holding the shell perpendicular to the grinding platform to create a flat surface for imaging.

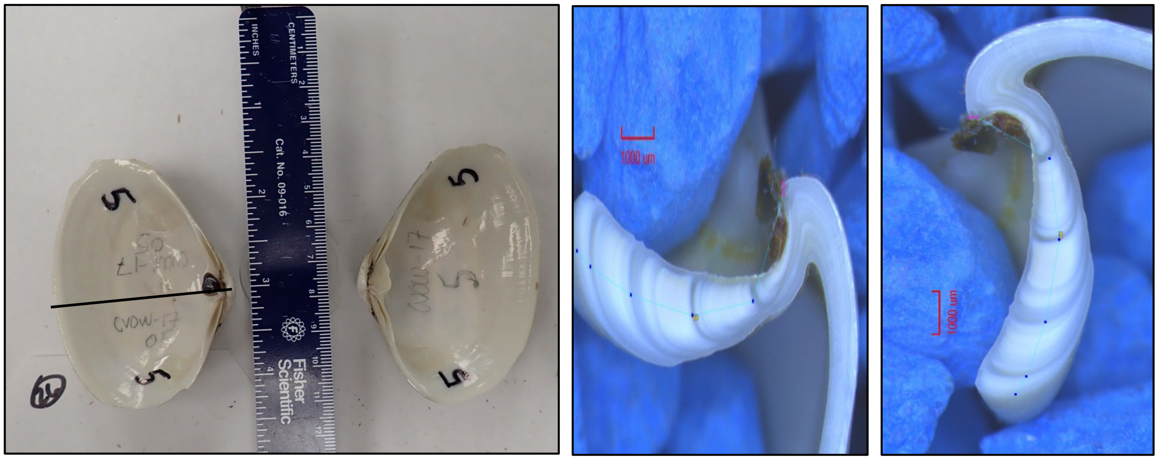


Figure 4: Surfclam shell processing for aging the chondrophore. (Left) Surfclam valves prepared for sectioning. Dotted line indicates where the surfclam shell is cut. (Middle)

Sectioning of surfclam using a tile saw. (Right) Sectioned chondrophore with annual rings marked.

After sanding and polishing, shells were imaged under an Olympus Microscope using Infinity Analyze software. Shells were aged by counting the number of growth lines along the chondrophore (Figure 4). This was done using Image J software with a tree ring application (ObjectJ) allowing the reader to place markers on each growth line, starting with the origin of the hinge and finishing with the growing edge. The origin, which is not an age ring, is marked with a pink point and all following growth lines are marked in blue (Figure 4).

Aged shells were used to build a relationship between age and length. The von Bertalanffy model was used to describe Atlantic surfclam growth as:

$$L_t = L_\infty (1- e^{-k(t-t0)}) \qquad \text{(Eq. 2)}$$

Where L_t is the total shell length at age t (mm), L_∞ is the theoretical asymptotic maximum length (mm), k is the growth coefficient (year− 1), and t0 is the theoretical age (years) at which length is zero. Individual ages were combined with shell strength data to evaluate how standardized shell strength varies with age. Unless otherwise specified, all statistical analyses were performed using R (version 3.6), and a p-value of <0.05 was considered statistically significant.

Results

Dredge Construction and Calibration

Paired Surveys

Across the 39 stations sampled in the 2022 survey, the *F.V. E.S.S. Pursuit* observed an average abundance of 0.066 surfclams/m2 (± 0.097 st. dev.), and an average biomass of 1.30 g/m2 (± 1.59 st. dev.). The *F.V. Joey D* observed an average abundance of 0.092 surfclams/m2 (± 0.13 st. dev.), and an average biomass of 1.96 g/m2 (± 2.74 st. dev.) per station. No significant difference was observed among the paired abundance of surfclams/m^2 (t-statistic=1.69, p=0.10, n=39) nor biomass/m^2 (t-statistic=1.79, p=0.081, n=38; one extreme outlier pair removed prior to analysis) observed by the two survey platforms (Figure 5).

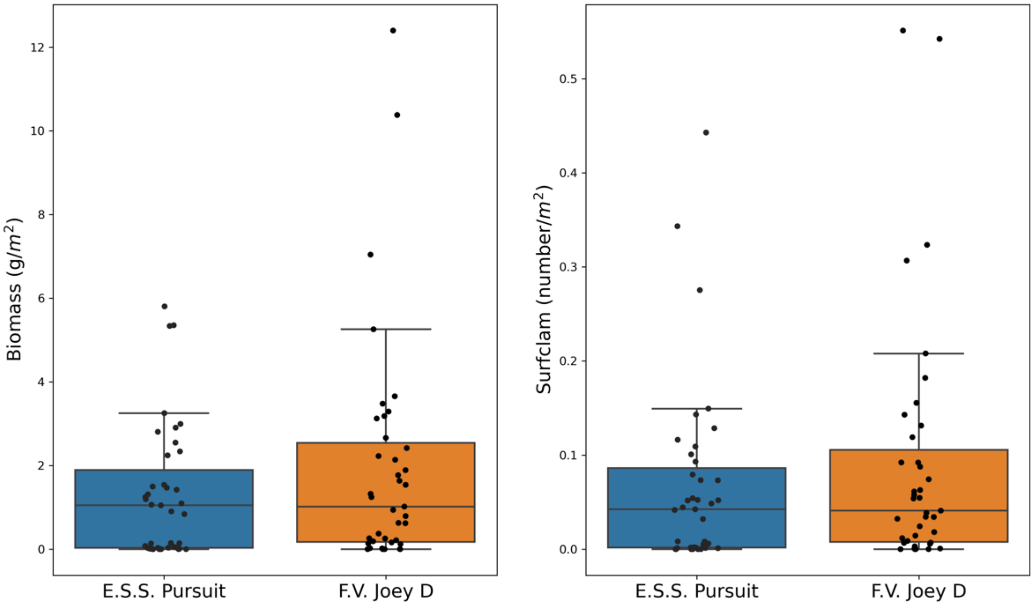


Figure 5: Boxplots of catch biomass (left) and abundance (right) for each tow (black circles) for the F.V. E.S.S. Pursuit (blue) and the F.V. Joey D (orange).

The shell length size frequency of the catch between the two platforms differed significantly (K-S = 0.13, p<<<0.0001, d.f.= 38). The surfclam sizes caught by the *F.V. Joey D* represented a wider range of sizes than that of the *F.V. E.S.S. Pursuit*, with both smaller and larger surfclams observed (Figure 6). The size selectivity ratio of the *F.V. Joey D* relative to the *F.V. E.S.S. Pursuit* varied by surfclam size with the *F.V. Joey D* showing higher selectivity for surfclams <90mm (3.5 in.) and >145mm (5.7 in.), and similarly for middle sizes of clams (Figure 6).

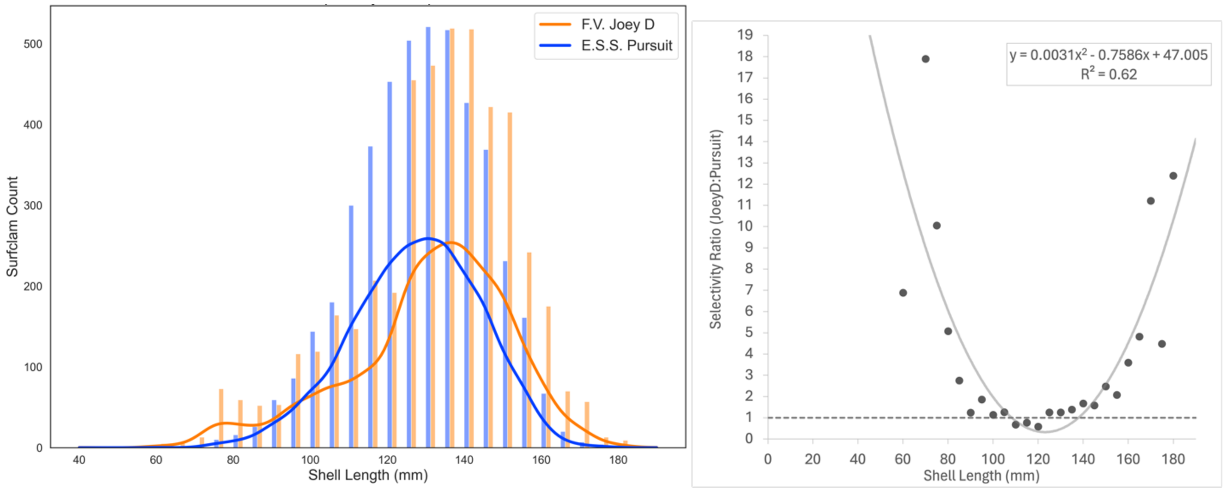
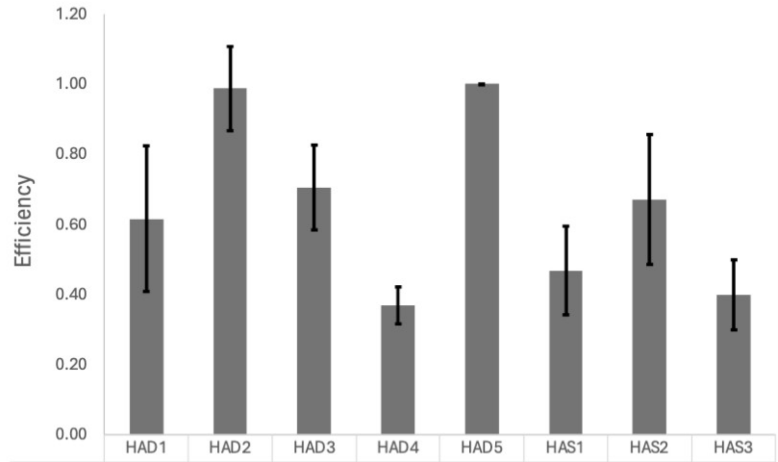


Figure 6: Histograms of surfclam sizes caught in each 5 mm size bin across all 39 stations in 2022 (left) for the F.V. E.S.S. Pursuit (blue) and F.V. Joey D (orange). The solid line overlaid on the histogram shows the smoothed distribution across all sizes. Selectivity ratio of the F.V. Joey D relative to the F.V. E.S.S. Pursuit for each 5 mm size bin shown with black dots (right), with an exponential curve fit to the data (grey line) and the 1:1 ratio line shown with the dotted horizontal line.

Depletion Experiments

Across the eight depletion experiments performed, the number of tows required to complete the experiments ranged from 14 to 29 (median=16, mean=19; Figure 7), and the maximum number of hits in each hit matrix ranged from 10 to 21 (median=13, mean=14; Figure 7,8). Efficiency estimated by the experiments ranged from 0.37 to 0.99 with an average efficiency across all experiments of 0.65 (± 0.24 st.dev.).



	HAD1	HAD2	HAD3	HAD4	HAD5	HAS1	HAS2	HAS3
■ Efficiency	0.62	0.99	0.71	0.37	1.00	0.47	0.67	0.40
Tows	14	16	16	29	15	23	15	21
Max Catch (n)	240	342	189	539	208	34	252	47
Max. Hits	11	12	13	21	13	16	10	15

Figure 7: Efficiency estimated from each depletion experiment; error bars show the standard deviation of each estimate. Table below the x-axis shows the number of tows required to complete the experiment, the maximum catch (number of surfclams), and maximum number of hits estimated by the hit matrix for each experiment.

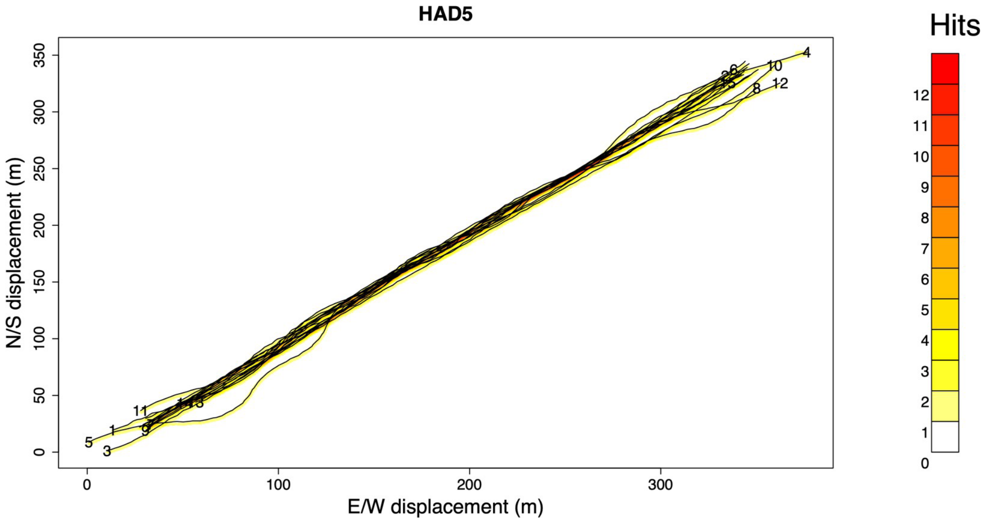


Figure 8: Overlapping track data from depletion experiment HAD5 with color scale indicating the number of tow hits for each grid. This experiment required 15 tows to achieve depletion and had a maximum of 13 hits.

Selectivity Experiment

Length frequency distributions of the catch show a similar range of surfclam sizes in both bar spacing conditions; however, the size distribution is skewed slightly left in the closed condition, indicating more small clams were caught in this configuration (Figure 9). Further analyses of these data are ongoing.

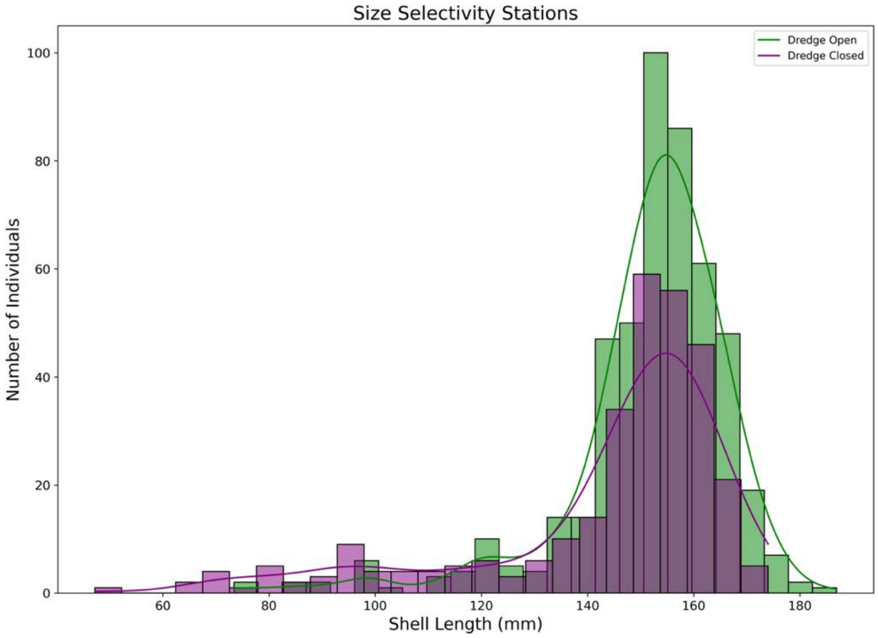


Figure 9: Length distributions of surfclams caught using the experimental dredge with bar spacing open (green; 4.4 cm between bars) and closed (purple; 2.0 cm between bars).

Surfclams and Bottom Water Conditions

Surfclam Population

Samples collected during dredge calibration efforts allowed us to characterize surfclam populations off the coast of New Jersey within and around several offshore wind lease areas prior to construction. The number of surfclams collected by dredge tow and by benthic grab tended to be higher at deeper stations; however, the abundances varied greatly with zero clams caught at some stations and up to 750 surfclams caught at others (Figure 10). The swept area abundance (i.e., total number of clams caught/swept area) ranged from 0 to 0.6 adult surfclams/m^2 across all stations sampled. Likewise, number of juvenile (<18mm shell length, <1 year old) surfclams retained in benthic grabs (0.1m^2 surface area) ranged from zero to 210 juvenile surfclams/m^2 (Figure 10).

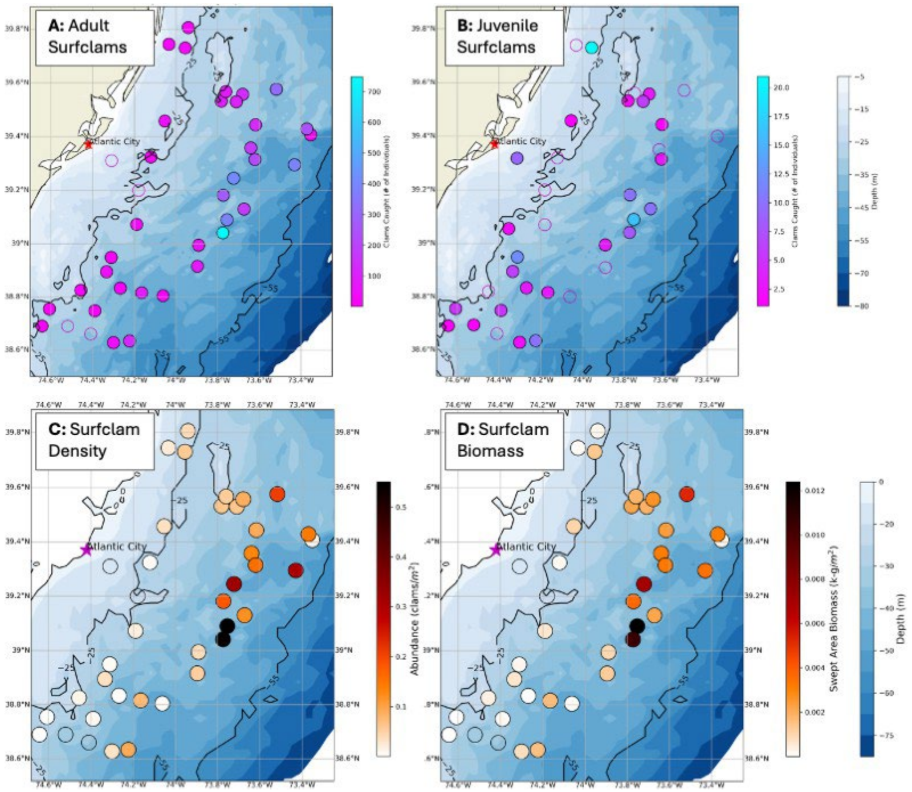


Figure 10: Map of surfclam catches from the 2022 survey off the New Jersey coast. A. numbers of adult surfclams caught per dredge tow shown; B. number of juvenile surfclams (<18mm shell length) caught per grab; C. swept area-corrected surfclam abundance (clams/m^2); D. swept area biomass (kg/m^2) of adult clams. Open circles indicate zero catch.

Length composition of the catch from the 2022 surveys also varied across stations. The largest clams tended to be found in higher proportions in the shallower stations, with a greater breadth of size classes represented in the southern and most eastern survey stations (Figure 11). Surfclams caught in the experimental dredge ranged in shell length from 35 mm (1.4 in.) to 189 mm (7.4 in.). Juvenile surfclams collected in grab samples ranged in shell length from 1.3 mm (0.05 in.) to 16.8 mm (0.7 in.). These variations in size could reflect differences in recruitment timing between fall and spring spawning events. Insufficient numbers of juveniles were collected at individual stations to examine spatial patterns in size distributions among stations; therefore, stations were parsed into two groups by depth (shallow stations were <31m deep, with 31m being the mean depth across all stations) and by latitude with the northern half of stations located north of 39.18°N, and the southern half located south of 38.18°N (the north/south dividing line intersects the New Jersey coast at Great Egg Harbor Inlet). Across all grabs, 147 juvenile surfclams were collected and measured. The median size observed was 5.4mm (mode = 3.7mm), and the size distribution varied little by depth and latitude; however, the largest juveniles collected were found in shallow central stations (Figure 12).

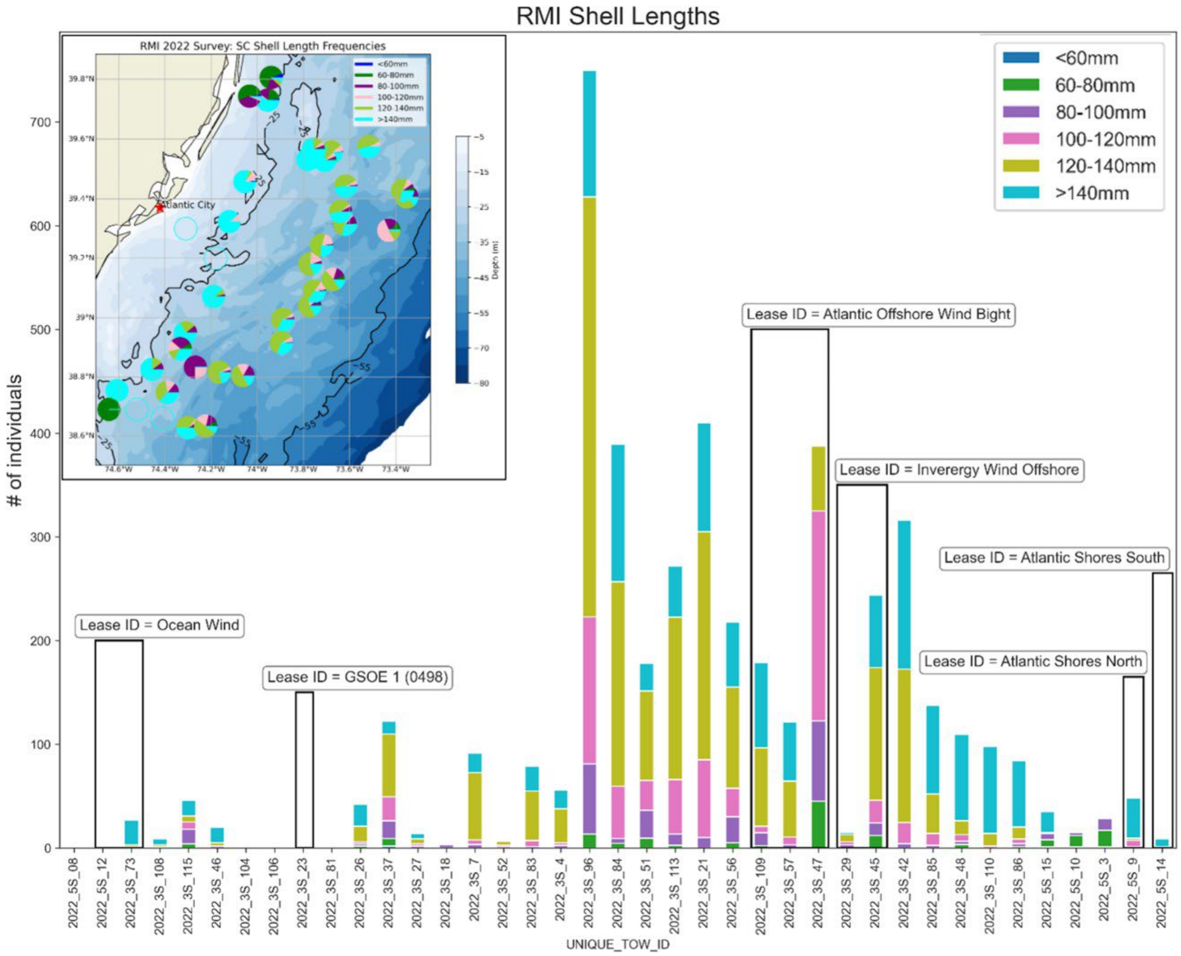


Figure 11: Length frequencies of adult clams caught in dredge tows in 2022 survey by station. Stations located within wind lease areas are annotated with a black box and the project name. Inset map at top left shows the proportion of the catch at each station by size group as pie charts. Open circles indicate no catch at that station. Raw data for each unique tow id name can be found in Appendix 2, and individual tows are listed here in sequential order occupied in the survey.

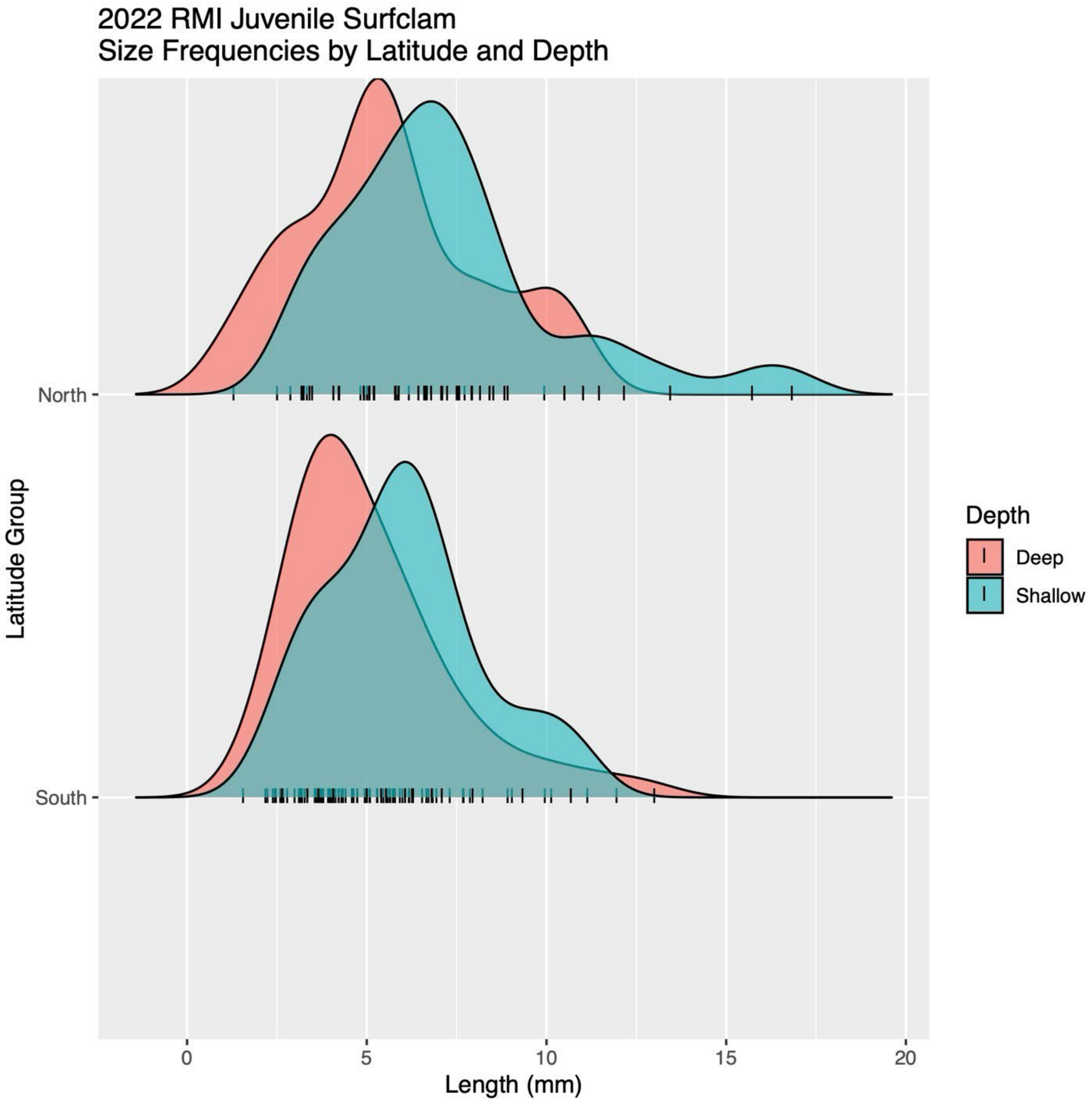


Figure 12: Patterns of juvenile surfclam size distribution across survey stations. Upper panel shows juveniles from northern stations and lower panel from southern stations with north and south divived at 39.18°N (the north/south dividing line intersects the New Jersey coast at Great Egg Harbor Inlet).. Pink probability distribution curves show deep stations, teal shows shallow stations (shallow stations were <31m deep, with 31m being the mean depth across all stations). Tick marks along the x-axis show individual observations.

Shell samples returned to the lab from the 2022 dredge survey were aged and measured. Ages observed ranged from 1 to 31 with most cohorts inbetween represented by at least 1 shell (only ages 27 and 29 were not observed). Using age and shell length observations from the 435 shells in the dataset, we fit a von Bertalanfy growth curve as shown in the figure below that predicts L_{inf}=152 mm and k=0.171 (Figure 13).

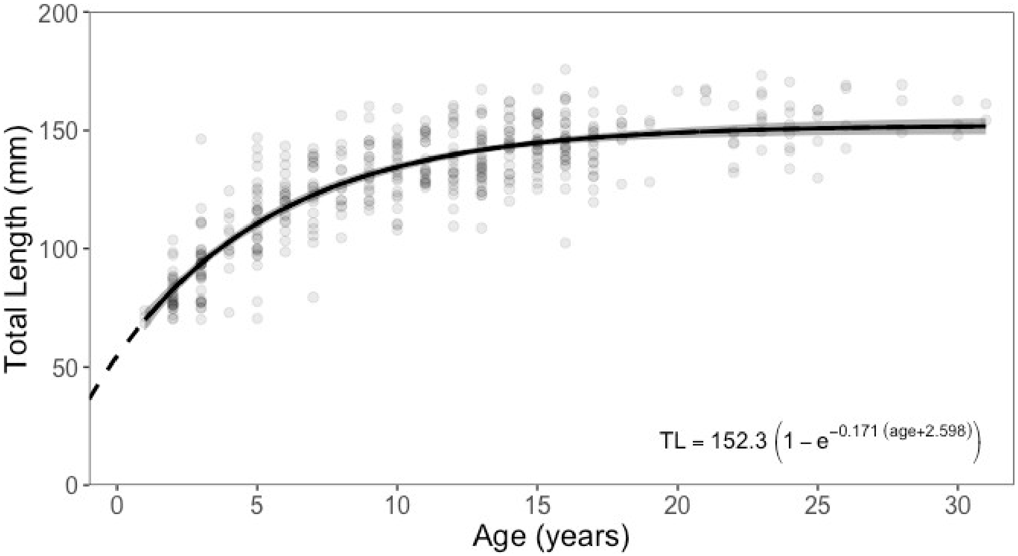


Figure 13: Age at length observed from shells collected in the 2022 survey. Grey circles indicate individual clam length and age. Black line shows the fitted growth curve, and the grey band indicates the 95% confidence interval for the fit.

Bottom Waters and Shell Strength

After comparing the pCO_2 sensor parameters measured in the field to those obtained from the bottle collection method, some large discrepancies were identified. We believe that in some cases this occurred because the 5 minutes we allowed for the sensor to equilibrate at a given depth was insufficient for the sensor to do so. The manufacturers recommendation for 5 minutes is inadequate when the pCO_2 environment is highly varied (e.g., large changes in pCO_2 from surface to bottom). Consequently, 2 of the stations with bottle comparisons in 2022 were unusable (one remained useable). In 2023, additional pCO_2 measurements were made using longer equilibration times (15 minutes at both surface and depth) which resulted in 3 stations at which direct comparison of carbonate chemistry from sensor data with discrete carbonate chemistry from bottle samples could be made. Across the four stations for which field accuracy of the pCO_2 sensor could be estimated, we determined the sensor overestimated omega aragonite (Ω_{Arag}) by 0.07 to 1.89. This overestimation, and the variability of this overestimation, is substantial, highlighting both poor sensor accuracy and precision. Although we report the results from field-collection of the sensor data below, these results should be considered with this sensor performance in mind. At 14 stations, bottom observations were compromised because the sensor remained within or moved in and out of the thermocline rather than remining constantly within bottom waters. Five other stations failed to retain clams for biological samples. For subsequent analyses, those 9 stations are removed from analysis and only bottom water observations are reported for the remaining (n=20) stations.

Spatial and interannual differences in temperature, pH, pCO2, and Ω_{Arag} were observed among the stations sampled in 2022 and 2023. Relatively lower pH and Ω_{Arag}, and higher pCO_2, were observed in bottom waters at stations closer to shore. Higher pH and Ω_{Arag}, and lower pCO_2 were observed across stations in bottom waters in 2023. Bottom water pH ranged from 7.6 to 8.1 across all stations (Figure 14), pCO_2 ranged from 425 µatm to 888 µatm across all stations, and average bottom Ω_{Arag} ranged from 0.68 to 5.07 across stations (Figure 14). Generally, the coldest bottom waters were located in the center areas of the continental shelf region surveyed, and the warmest waters occurred at stations further offshore.

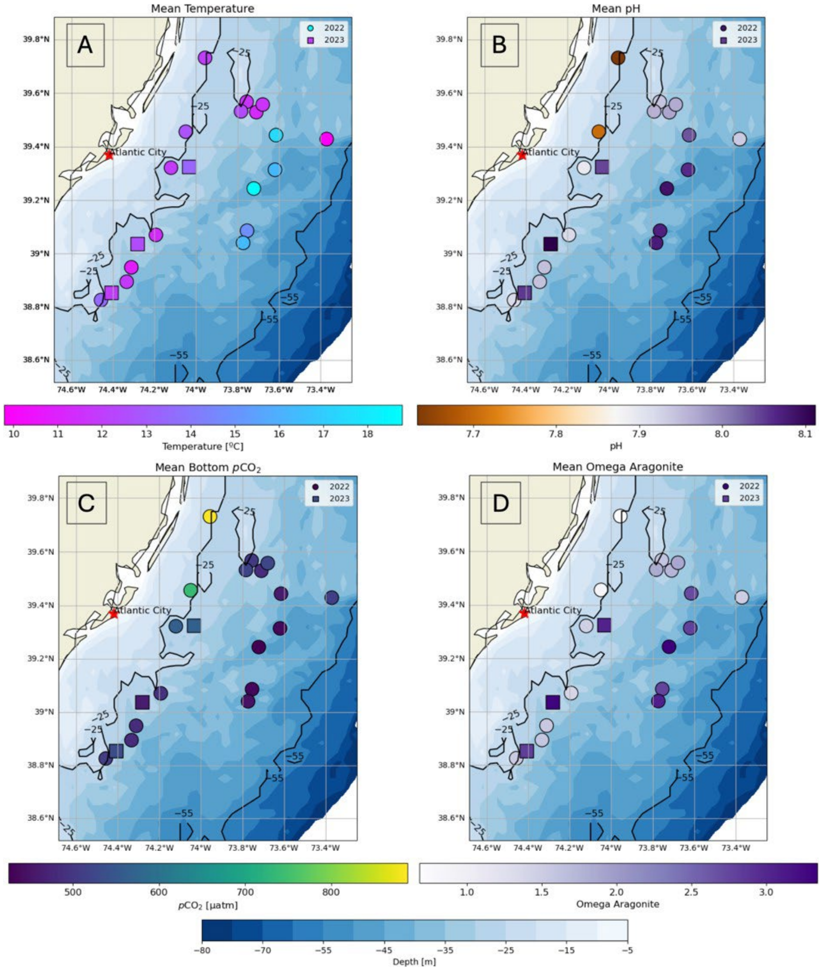


Figure 14: Average bottom (A) temperature, (B) pH, (C) pCO_2, and (D) Ω_{Arag}, at stations where carbonate chemistry parameters and Atlantic surfclams were collected. Colorbars below each panel represent the observed range of data in each map, circles show stations occupied in 2022, squares show stations occupied in 2023.

Shell strength also varied by station, with the maximum strength observed at 0.45 kN and the minimum was 0.01 kN (mean ± SD = 0.116 ± 0.07 kN). Shell weights ranged 2.6-203.2 g, and shell thickness ranged 1.02-7.62 mm. Standardized shell strength ranged from 0.00035 kN/g to 0.00588 kN/g (mean ± SD = 0.00186 ± 0.00074 kN). No significant correlations were observed between standardized shell strength and pH (p-value = 0.28; d.f. = 16; F = 1.25; Adj. R2 = 0.015), pCO2 (p-value = 0.47; d.f. = 16; F = 0.56; Adj. R2 = -0.028), ΩArag (p-value = 0.175; d.f. = 16; F = 2.02; Adj. R2 = 0.06), nor temperature (p-value = 0.25; d.f. = 16; F = 1.41; Adj. R2 = 0.025) (Figure 15). These results support the null hypothesis that the observed bottom water carbonate chemistry conditions at each station are not correlated with average standardized shell strength. However, standardized shell strength is non-linearly related to age, with youngest clams showing the strongest shells when strength is standardized by shell weight (Figure 16); therefore, additional analyses should be run to evaluate the influence of environment that includes age as a covariate.

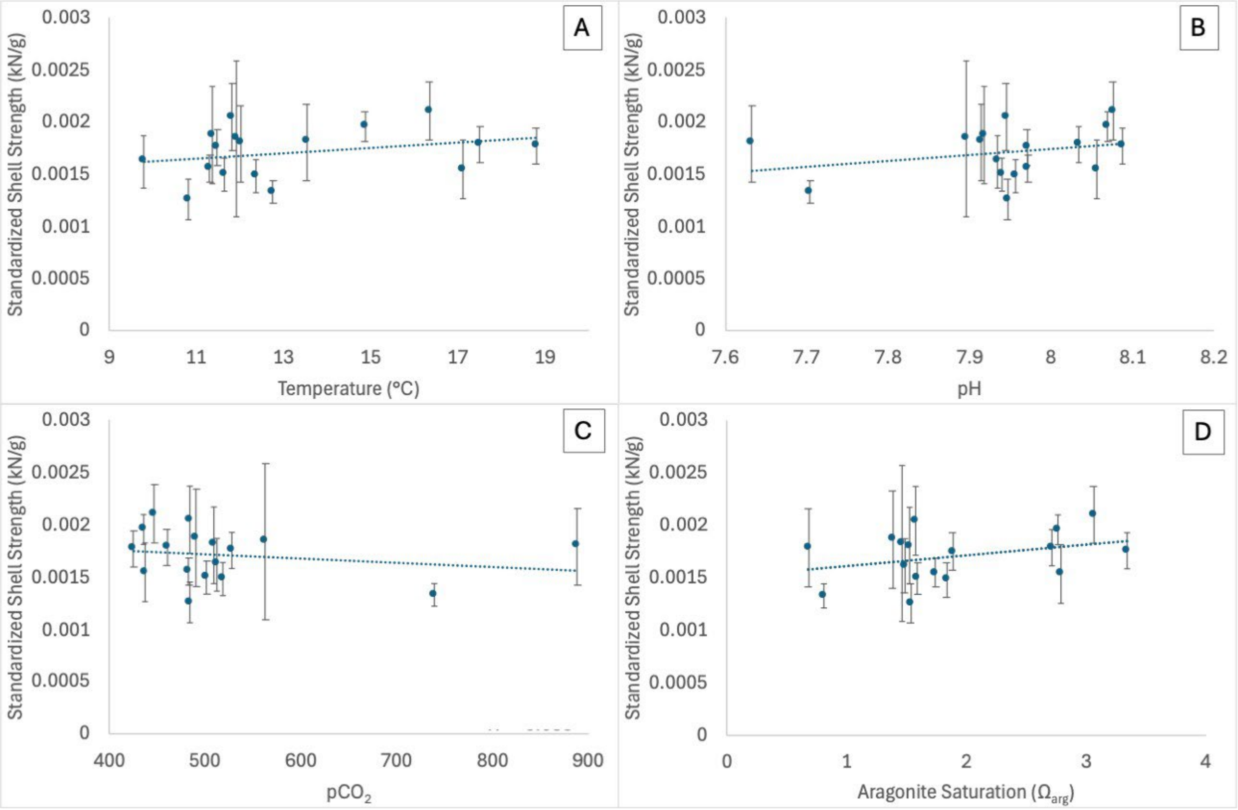


Figure 15: Carbonate chemistry parameters, (A) temperature, (B) pH, (C) pCO₂, and (D) Ω$_{Arag}$, relative to the average shell strength standardized by shell weight (kN/g) at each station observed in 2022. Error bars indicate the 95% confidence interval of the average standardized shell strength.

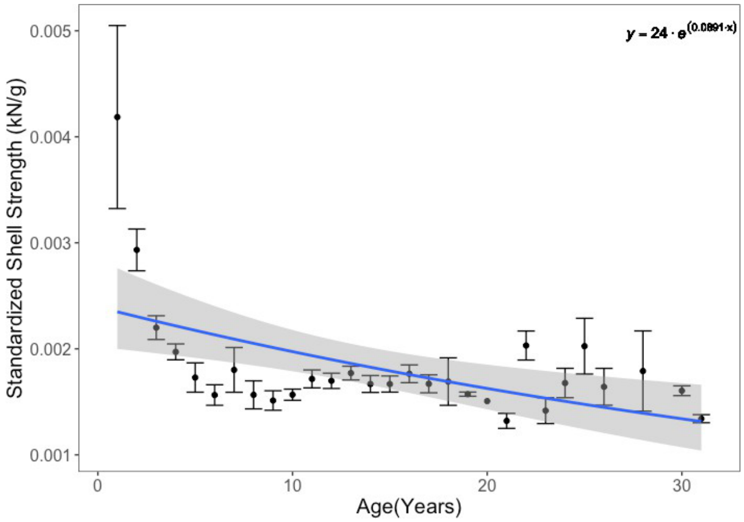


Figure 16: Average standardized shell strength by age class for all surfclam shells collected in 2022. Error bars represent 95% confidence intervals.

Data Management

On each of the cruises, a master log of all samples collected was recorded on physical data sheets (printed on waterproof paper) that were later scanned and data entered into a master log file. All biological data collected on the vessel (shell lengths, catch volumes, station location, tow duration) was recorded on a digital spreadsheet on board. All digital data files were backed up on an external drive at the end of each watch, and further backups made upon return to the laboratory. All data collected on sampling trips, and all subsequent data collected in the laboratory were checked for quality control by independent technical staff following lab protocols. Data from the project have been assembled and organized into summary files that contain trip, station, and tow-level biological and water quality data. These summary data files have been served on a public server (access it here using search term 'clam') and are appended at tables at the end of this report.

Leveraged Products

One of the main goals of this project was to develop and characterize a scientific survey tool for use in monitoring surfclam populations in and around offshore wind lease areas. This survey tool, the experimental hydraulic dredge, was successfully developed and calibrated in several ways. Since its development, this experimental survey dredge has been used in a standardized way at other offshore wind lease areas to provide data about surfclam populations before construction of the offshore wind projects began. These additional surveys have been funded by offshore wind companies as part of their fishery monitoring programs. The lease areas at which this dredge has been used, the years surveyed, and the reports produced to date are provided in Table 1. For all the offshore wind surfclam surveys to date using this dredge, the data have been served publicly at the same repository the data from this project are located (access it here using search term 'clam'). In addition to surveys completed to date, several additional offshore wind developers have inquired about the possibility of using this fully calibrated surfclam survey platform for clam fishery monitoring within and around their project areas.

Table 1: Offshore wind lease areas at which the experimental dredge has been used, the years surveyed, and reports produced to date.

Lease	Project Name	Years Surveyed	No. of Stations	Report
OCS-A 0498	Ocean Wind 1	2022, 2023	78	Pending
OCS-A 0483	Coastal Virginia Offshore Wind	2023	39	Here
OCS-A 0499	Atlantic Shores South	2024	46	Pending

Discussion

Dredge Construction and Calibration

Under this project's funding, the experimental dredge was successfully constructed following the schematics designed through fishing industry collaboration. When compared to the federal surfclam survey platform, the new experimental dredge samples clams similarly in terms of overall dredge efficiency. Using depletion experiments conducted in 2023, average efficiency estimates were determined to not be significantly different; the *F.V. E.S.S. Pursuit* was previously estimated to be 0.67 (NEFSC, 2017) and the *F.V. Joey D* was estimated to be 0.65 (results of this project). Estimates of survey gear capture efficiency allow absolute abundance to be inferred from observations of catch per unit effort (Delargy et al., 2023), allowing integration of the data collected among different surveys so long as each gear has its own independently determined efficiency estimate. Size selectivity differs among the two platforms with the *F.V. Joey D* catching the smallest and largest size classes of surfclams more effectively than the *F.V. E.S.S. Pursuit*. These slight differences in the amount and sizes of catches among the two survey platforms could be related to several factors including possible differences in the captains' operation of vessels and the size and weight of each dredge relative to the vessel carrying it. The *F.V. Joey D* is a smaller boat with a heavy, but small, dredge, which might make for better control over tow track location and better bottom contact on average. The catch performance data collected in this program will support the use of survey data collected by this new experimental dredge to be directly compared to data collected by other calibrated survey platforms.

The experimental dredge has already proven to be an important survey tool for offshore wind fishery monitoring programs. On the first fishery monitoring survey sampling trip using the experimental dredge (a survey of Ocean Wind 1, 2022, funded by the developer), the dredge proved to effectively sample a broad size range of clams from the bottom while minimizing capture of additional shell and other debris as would occur with a lined dredge. On the second survey using this dredge (a survey of CVOW, 2023, funded by the developer) substantial surfclam biomass was observed at the southern edge of the species range that has otherwise been missed by surveys because the size of the clams at this southern range boundary are smaller than is typically caught. The efficacy of the experimental dredge as a survey tool is demonstrated by its use thus far in three surfclam surveys (see Table 1) conducted as part of fishery monitoring programs (a fourth is underway at the time of this report). Several additional offshore wind developers have expressed interest in use of this dredge to survey their leases in the future as construction plans continue to advance. Surfclam fishing activities and stock habitat overlaps most of the wind lease areas in the Mid Atlantic, and given the technical needs or clam surveys, this survey platform is uniquely well-suited to sampling individual lease areas in support of regionally integrated fisheries monitoring for clams.

Although the experimental dredge construction and calibration supported by this project were successful, the survey vessel used for those calibrations (*F.V. Joey D*) is a relatively small vessel in comparison to some in the fleet, with limited berthing for science crew and survey endurance capacity challenges due to the amount of freshwater, provisions, and fuel it can carry. Existing offshore wind leases and areas planned for offshore wind leasing cover 8% (22.237 million acres) of the total benthic habitat of the Atlantic outer continental shelf (BOEM, 2022), with 708 ha of scour protection (excluding New York Bight leases; Borsetti et al., 2023) and extensive cabling that will alter soft-sediment benthic habitats essential for surfclams and other shellfish (Stokesbury et al., 2024). The substantial overlap of offshore wind lease areas with important surfclam habitat and fishing grounds (Kirkpatrick et al., 2017; Scheld et al., 2022; Stokesbury et al., 2024) warrantsthe need for surfclam surveys to be part of fishery monitoring plans for these extensive areas. Should the need for clam surveys expand in correspondence with offshore wind development, additional calibrated survey capacity will be needed. Performing experiments to support expanded surfclam survey efforts to ensure that capacity is available in advance of project construction should be a research priority given the importance of the surfclam fishery to the state of New Jersey.

Surfclams and Bottom Water Conditions

Samples of surfclams collected in this program provide valuable biological and ecological information for the population of surfclams off New Jersey, in and around offshore wind lease areas. Surfclams collected in our experiments include age classes from < 1 year old (collected in benthic grabs) through 31 years old, which represents the range of the life history given that they live to a maximum of ~35 years (Munroe et al., 2016). All age classes were consistently observed across the stations sampled in 2022, suggesting that recruitment of surfclams has been consistent in federal waters off New Jersey in recent decades. Recruitment is the mechanism by which a population replaces losses from mortality, and in long-lived species, consistent recruitment serves to support population stability (Pace et al., 2017). Population densities >0.5 clams/ m^2 are considered sufficient to make commercial fishing viable (Powell et al., 2016; Powell et al., 2017) and the abundance estimates observed in this study ranged from 0 to 0.6 adult surfclams per m^2 with highest densities collected across this survey at stations further offshore and northward. Observation of continued year class recruitment over the 3 decade life span, and population densities sufficient to support the commercial fishery, indicates a healthy surfclam population off the coast of New Jersey.

In addition to evaluating the population status for surfclams off New Jersey, this project aimed to better understand the response of surfclams to climate stressors such as carbonate chemistry in bottom water surfclam habitats. Although biological sampling in this program for this goal was successful (i.e., collecting clams, assessing age, measuring shell strength, etc.), after comparing the $p\mathrm{CO}_2$ sensor parameters measured in the field to those obtained from the bottle collection method, some large discrepancies were identified. We believe that in some cases this occurred because the manufacturer's recommendation guidance for sensor equilibration at a given depth was insufficient for the sensor to operate accurately. Across our comparisons of the $p\mathrm{CO}_2$ sensor to bottle data, the sensor consistently, and significantly, overestimated ΩArag. Additionally, several of the stations at which we attempted to measure bottom water conditions, post-processing of data revealed that the sensor was sampling well off the bottom and those stations had to be removed from further analysis. Ultimately, a smaller and less reliable data set than anticipated was used for analyzing correlation between clam biological metrics and bottom water conditions, and these initial results should be confirmed with additional study. Although studies have evaluated shell structure and chemistry responses to changing carbonate chemistry (Milano et al., 2016; Cameron et al., 2020; Armstrong, et al., 2022), most have done so in controlled laboratory conditions and not in natural environments (Grear et al., 2020). These 'real world' responses of bivalves to ocean acidification are critical to our interpretation of laboratory results and for anticipation of future impacts of climate stressors. Therefore, it is our recommendation that field studies about stress responses continue, and that they are conducted with sensors with faster response time and higher accuracy/precision for pH and $p\mathrm{CO}_2$ to support co-located environmental and biological data.

Furthermore, after analysis of data collected to date, it appears that shell strength may not be the ideal parameter with which to determine stress in surfclams because it is a physiological metric that derives from integrated environmental conditions over long periods of time. Other biological parameters such as body condition (e.g. Zhao et al., 2019) and transcriptomic responses (e.g. Acquafredda et al., 2024) may be better able to illuminate the response of surfclams to short-term stressful conditions, such as seasonal or episodic warming or acidification and/or development of offshore wind. In addition, recent glider observations revealed low dissolved oxygen in bottom waters that occurred concurrently with low pH/Ω_{Arag} and low dissolved oxygen (NEFSC, 2024), which are conditions known to be stressful for surfclams (Steeves et al.,2024; Vaquer-Sunyer & Duarte, 2008). Adding dissolved oxygen to the suite of parameters measured will help improve the interpretation of co-located bottom water and biological data. Future research should consider multiple environmental stressors and how shellfish respond on individual and population levels to those stressors.

Deliverables

To date, this project has generated 1 peer-reviewed publication, a second that is in review, and one conference paper. The project has supported one completed Masters student thesis, and two PhD student dissertations that are in progress. Five undergraduate students have been engaged in the project by participating in field, laboratory, or data processing. Several project presentations have been made, including presentations to regional offshore wind networks (ROSA), NJDEP, and RMI, as well as presentations at regional and national science conferences.Survey data including surfclam abundances and oceanographic bottom water conditions are provided in Appendix 1 in tabular format, and in digital download format at https://rowlrs-data.marine.rutgers.edu/erddap/index.html (use search term 'clam').

Peer-reviewed papers generated from this project:

1. Munroe, D., Borsetti, S., Sheehan, A., Piper, S., Morson, J., Hennen, D. Estimating Efficiency of a Scientific Clam Survey Dredge: Strategies for an Improved Experimental Approach. *In Review:* Fisheries Research.
2. Munroe, D., Morson, J., Borsetti, S., Hennen, D. 2023. Sampling High Biomass but Rare Benthic Animals: Methods for Surveying Commercial Clam Stocks Using a Hydraulic Dredge. Fisheries Research, 258: 106538

Conference Papers:

1. DiRenzi, B., Munroe, D., Saba, G., and A. López, Biological Response of *Spisula solidissima* (Atlantic Surfclams) to Varying Carbonate Chemistry in the Mid-Atlantic Bight," *OCEANS 2023 - MTS/IEEE U.S. Gulf Coast*, Biloxi, MS, USA, 2023, pp. 1-7

Technical Reports:

1. Munroe, D., Borsetti, S., Sheehan, A., Piper, S., Morson, J., Hennen, D. 2024. Efficiency of a scientific clam survey dredge and strategies for an improved experimental efficiency approach. Report to New Jersey Research and Monitoring Initiative, Project BC22-001-001.
    - Available on NJDEP RMI website at https://dep.nj.gov/wp-content/uploads/offshorewind/docs/njdep-surfclam-technical-report.pdf

Student Theses & Dissertations:

1. DiRenzi, Breana. 2023. Biological response of *Spisula solidissima* (Atlantic surfclams) to varying carbonate chemistry in the Mid-Atlantic Bight. Master's of Operational Oceanography Thesis, Rutgers University, 30pp.

Project Presentations:

1. Piper, S., Sheehan, A., Borsetti, S., Morson, J., Saba, G., Munroe, D. 2024. An Improved Approach to Dredge Depletion Experiments to Support Regional Clam Surveys. Poster presentation at NYSERDA State of the Science Symposium, July 16-19, 2024.
2. Munroe, D., Morson, J., Borsetti, S., Saba, G. 2024. Monitoring Surfclams at Offshore Wind Energy Project Sites in the Mid-Atlantic. Poster presentation at NYSERDA State of the Science Symposium, July 16-19, 2024.
3. Tanaka, H., Piper, S., Munroe, D. 2024. Size and Abundance of Juvenile Atlantic Surfclams (*Spisula solidissima*) in Wind Lease Areas Offshore of New Jersey. Poster Presentation at NYSERDA State of the Science Symposium, July 16-19, 2024.

4. Munroe, D., Morson, J., Borsetti, S., Saba, G. 2024. Monitoring Surfclams at Offshore Wind Energy Project Sites in the Mid-Atlantic Poster presentation at Ocean Sciences, New Orleans, LA, Feb. 19-23, 2024.
5. Munroe, D., Morson, J., Borsetti, S., Saba, G. 2023. Monitoring Surfclams at Offshore Wind Energy Project Sites in the Mid-Atlantic. Oral presentation at American Fisheries Society Mid-Atlantic Chapter Annual Meeting, Wilmington, DE, November 16-17, 2023.
6. Sheehan, A., Piper, S., Borsetti, S., Morson, J., Munroe, D. 2023. An Improved Approach to Dredge Depletion Experiments. Poster presentation at American Fisheries Society Mid-Atlantic Chapter Annual Meeting, Wilmington, DE, November 16-17, 2023.
7. DiRenzi, B., Munroe, D., Saba, G., López, A. 2023. Biological Response of *Spisula Solidissima* (Atlantic Surfclams) to Varying Carbonate Chemistry in the Mid-Atlantic Bight. Oral presentation at the MTS Oceans 2023 meeting. Biloxi, MI. September 2023.
8. Munroe, D., J. Morson, G. Saba. 2023. Monitoring surfclams at offshore wind energy projects. Oral presentation at 115th Annual Meeting of the National Shellfisheries Association, Baltimore, MD, March 27 – 30, 2023.
9. Munroe, D. 2023. Surveys and Experiments for Monitoring Surfclams at Offshore Wind Projects. Oral presentation at the Rutgers Offshore Wind Symposium, New Brunswick, NJ, Jan, 12, 2023.

Conclusions and Recommendations for Future Research

Although this study was not designed specifically to collect pre-construction data, stations occupied in these experiments include several within and adjacent to offshore wind lease areas and therefore can contribute to the assessment of surfclam populations before construction. In addition, the availability of multiple survey platforms with known efficiency supports data comparison among platforms, allows integration of datasets over time, and offers platform redundancy. The calibrated survey platform supported by this RMI project adds new surfclam survey capacity to the region that has already been used in several offshore wind fishery monitoring programs. We anticipate that this platform will continue to support monitoring into the future as offshore wind development advances in the region and generates additional need for fishery monitoring programs. Increased capacity for data comparison and integration will support our ability to investigate regional patterns in stock biology and status that go beyond that available from a single survey platform, helping us understand the dynamics of commercially important stocks as they respond to changing ocean conditions and growth of offshore wind.

By developing new survey tools and by addressing gaps in our understanding of the biological response of the surfclam fishery stock to changing bottom water conditions, this project supports the New Jersey Offshore Wind Research and Monitoring Initiative (NJ RMI) short-term highest-priority research areas 3 (Benthos) and 13 (Fisheries). This project aligns with the vision of the NJ RMI by directly supporting offshore wind monitoring efforts and aiming to characterize the mechanisms underlying interactions among offshore wind construction and operations and key resources of economic importance to the state of NJ. Consistent with the goals of the NJ RMI, this project employed best available science to conduct this research cooperatively with the commercial fishing sector to maximize its relevance and engagement with that stakeholder group. Given the commercial and economic importance of the surfclam fishery to New Jersey, this project will benefit the state by supporting a better understanding of the benthic resources supporting the stock, and how that may or may not change with growth of offshore wind.

Our recommendations for future research support the need for expanded survey capacity as offshore wind footprints grow, and that field studies about surfclam environmental stress responses continue with higher accuracy/precision pH and $p\mathrm{CO}_2$ sensors and considering individual and population level responses to multiple environmental stressors.

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Appendices

Appendix 1: Data Tables

Table A1: Catch summaries from 5 minute tows at paired station sites in 2022.

Station Name	Day	Month	Year	Time (GMT)	Latitude	Longitude	Tow Area (m^2)	Surfclam Catch Volume (42L bushels)	Number Surfclams Caught	Bottom Temperature (□C)	Shell Length (mm) Min – Max (Ave)
5S_8	19	8	2022	23:17:35	39°18.496'	74°18.925'	1798	0	0	17.8	-
5S_12	20	8	2022	1:05:59	39°12.088'	74°10.976'	1399	0	0	12.8	-
3S_73	20	8	2022	2:50:38	39°4.238'	74°11.580'	1490	0.5	27	11.6	94.1-169.8 (151)
3S_97	20	8	2022	4:19:16	39°3.323'	74°21.189'	446	No catch	No catch	11.7	-
3S_108	20	8	2022	5:46:58	38°56.924'	74°18.678'	1318	0.25	9	10.9	86.4-174 (144)
3S_115	20	8	2022	7:08:35	38°53.679'	74°20.020'	1367	0.5	46	11.8	73.8-162.4 (118)
3S_46	20	8	2022	8:43:13	38°49.527'	74°27.440'	1713	0.33	20	13.8	90.6-168.5 (146)
3S_104	20	8	2022	10:31:18	38°45.388'	74°36.357'	1653	0.001	1	12.8	147.5-147.5 (148)
3S_106	20	8	2022	11:50:37	38°41.307'	74°38.503'	1517	0.001	1	12.9	65.6-65.6 (66)
3S_23	20	8	2022	13:16:24	38°41.577'	74°31.225'	1434	0	0	10.3	-
3S_81	20	8	2022	14:34:27	38°39.881'	74°24.912'	1149	0	0	12.0	-
3S_26	20	8	2022	16:09:17	38°37.571'	74°17.930'	1301	0.5	42	12.7	65-155.9 (134)
3S_37	20	8	2022	17:29:56	38°37.962'	74°13.131'	1313	1	122	12.7	57.4-160.5 (118)
3S_27	20	8	2022	19:10:18	38°44.786'	74°23.415'	1607	0.1	14	12.6	91.2-155.5 (128)
3S_18	20	8	2022	20:45:34	38°49.915'	74°15.959'	1336.	0.001	4	19.8	83.8-103.8 (94)
3S_7	20	8	2022	22:00:07	38°48.828'	74°9.835'	1226	1.1	91.3	14.2	90.2-160.1 (131)
3S_52	20	8	2022	22:53:36	38°48.265'	74°3.743'	1200	0.001	8	NA	93.7-143.6 (123

3S_83	20	8	2022	0:45:12	38°54.927'	73°53.757'	1467	1	79	NA	90.4-155.6 (133)
3S_4	20	8	2022	1:44:12	38°59.627'	73°53.378'	1449	0.67	56	17.6	95.5-155.5 (135)
3S_96	20	8	2022	2:56:59	39°2.442'	73°46.396'	1381	6.75	749.25	16.3	70.9-151.1 (125)
3S_84	21	8	2022	3:59:45	39°5.169'	73°45.259'	708	4.75	389.5	18.4	75.5-157.6 (132)
3S_51	21	8	2022	5:12:24	39°7.712'	73°40.470'	1496	2	178	17.8	70.6-157.4 (121)
3S_113	21	8	2022	6:19:48	39°10.886'	73°46.257'	1495	2.75	272.25	18.5	77.5-155.5 (127)
3S_21	21	8	2022	7:30:45	39°14.654'	73°43.304'	1351	5	410	18.5	93.9-162.7 (130)
3S_56	21	8	2022	8:56:34	39°18.856'	73°37.182'	1351	2.5	217.5	19.1	74.3-162.3 (128)
3S_109	21	8	2022	9:54:05	39°21.459'	73°38.373'	1351	2.1	178.5	19.7	79.4-156.8 (134)
3S_57	21	8	2022	11:06:10	39°26.624'	73°36.889'	1325	1.5	121.5	17.2	84-188.6 (138)
3S_47	21	8	2022	13:50:38	39°17.670'	73°25.820'	1265	2.5	387.5	12.3	62.3-137.3 (105)
3S_29	21	8	2022	15:38:40	39°24.362'	73°20.987'	1044	0.1	15	18.1	91.1-157.6 (122)
3S_45	21	8	2022	16:23:21	39°25.747'	73°22.266'	1708	2	244	9.6	65.7-164.1 (129)
3S_42	21	8	2022	18:17:06	39°34.535'	73°31.040'	1519	4	316	NA	80.6-162.4 (137)
3S_85	21	8	2022	19:58:20	39°33.468'	73°40.730'	1576	2.25	137.25	11.5	82.5-170.5 (144)
3S_48	21	8	2022	20:50:36	39°31.766'	73°42.584'	1671	1.5	109.5	11.3	71.8-167.9 (144)
3S_110	21	8	2022	21:52:19	39°31.946'	73°46.994'	1599	2	98	11.8	118.7-179.6 (154)
3S_86	21	8	2022	22:35:24	39°34.070'	73°45.373'	1540	1.25	83.75	12.1	72.8-170.1 (146)
5S_15	21	8	2022	1:05:18	39°43.889'	73°57.375'	762	0.33	35	12.1	55.2-179 (123)
5S_10	21	8	2022	2:10:06	39°48.4558'	73°56.365'	489	0.05	17	12.0	36.4-154.1 (82)
5S_3	21	8	2022	3:18:18	39°44.585'	74°2.069'	1237	0.05	30	16.1	56-140.3 (82)
5S_9	22	8	2022	6:16:30	39°27.386'	74°2.953'	1396	0.75	48	12.9	57.4-171.8 (143)
5S_14	22	8	2022	9:10:15	39°19.327'	74°7.227'	1586	0.1	9	12.2	101-158.7 (142)

Table A2: Average bottom water conditions and average shell strength at stations where carbonate chemistry parameters and Atlantic surfclams were collected. Aragonite is estimated using measured pH, pCO2, temperature, salinity, and pressure using PyCO2SYS package in Python. Stations for which no clams were caught, or for which observations were not reflective of bottom conditions are not included in this table.

Station Name	**Date Sampled**	**Latitude**	**Longitude**	**Temperature (ºC)**	**pH**	**Partial Pressure CO_2**	**Ω Aragonite**	**Average Standardized Shell Strength (kN/g)**
3S_108	Aug. 20, 2022	38.9487459	-74.31131	10.8	7.9	484.2	1.53	0.00125
3S_110	Aug. 21, 2022	39.5324451	-73.783241	12.4	8.0	518.0	1.83	0.00148
3S_115	Aug. 20, 2022	38.8946555	-74.333668	11.8	7.9	483.8	1.57	0.00204
3S_21	Aug. 21, 2022	39.2442381	-73.721737	18.8	8.1	425.0	3.34	0.00176
3S_45	Aug. 21, 2022	39.4291233	-73.371101	9.8	7.9	512.4	1.48	0.00161
3S_46	Aug. 20, 2022	38.825465	-74.457336	13.5	7.9	508.8	1.52	0.00180
3S_48	Aug. 21, 2022	39.5294478	-73.709743	11.3	8.0	482.9	1.74	0.00155
3S_56	Aug. 21, 2022	39.3142702	-73.619703	17.1	8.1	437.3	2.79	0.00154
3S_57	Aug. 21, 2022	39.4437449	-73.614823	17.5	8.0	459.9	2.71	0.00178
3S_73	Aug. 19, 2022	39.0706472	-74.193013	11.4	7.9	490.8	1.38	0.00187
3S_84	Aug. 21, 2022	39.0861663	-73.75433	14.9	8.1	435.4	2.76	0.00195
3S_85	Aug. 19, 2022	39.5578107	-73.678843	11.5	8.0	527.6	1.88	0.00175
3S_86	Aug. 19, 2022	39.5678383	-73.756229	11.6	7.9	501.6	1.59	0.00149
3S_96	Aug. 20, 2022	39.0407088	-73.77327	16.3	8.1	446.8	3.06	0.00210
5S_09	Aug. 19, 2022	39.4564477	-74.049221	12.8	7.7	739.4	0.81	0.00132
5S_14	Aug. 22, 2022	39.3221265	-74.120452	11.9	7.9	562.6	1.46	0.00183
5S_15	Aug. 21, 2022	39.7314919	-73.956265	12.0	7.6	888.3	0.68	0.00178
CS2_93	Aug. 14, 2023	38.8540626	-74.407431	12.0	8.1	531.9	4.41	0.00187
S2_41	Aug. 14, 2023	39.0375724	-74.281987	12.5	8.1	461.6	5.07	0.00141
XTRA	Aug. 14, 2023	39.3259117	-74.03457	13.4	8.0	565.7	4.53	0.00142

Appendix 2: Quality Assurance Project Plan (QAPP)

New Jersey Department of Environmental Protection Division of

Science and Research (DSR)

Quality Assurance Project Plan (QAPP)

for

Calibration Experiments for a Novel Clam Survey Dredge and Monitoring Carbonate Chemistry of Surfclam Habitat

Contract No. BC22-001 (Task Order No. 001)

Dr. Daphne Munroe, Rutgers University (Haskin Shellfish Research Lab), Principal Investigator

Signature:____ Date:___06/06/2022___

Dr. Jason Morson, Rutgers University (Haskin Shellfish Research Lab), Principal Investigator

Signature:___ ________________________________Date:___6/6/22

Dr. Grace Saba, Rutgers University (Department of Marine and Coastal Sciences), Principal Investigator

Signature: ____ Date: 06/06/2022

Dr. Reneé Reilly, NJDEP (Division of Science and Research), Project Manager Signature:_

Date: 6/14/2022 Renee Reilly _______________

Ms. Colleen Brust, NJDEP (Marine Resources Administration), Project Manager Signature:

Colleen Brust ____ Date: 6/14/2022

Dr. R. Lee Lippincott, NJDEP (Division of Science and Research), Quality Assurance Officer

R. Lee Lippincott Ph.D.

Signature:____Date:____6/8/2022____________

Project Information Page:

1. Project Name: Calibration Experiments for a Novel Clam Survey Dredge and Monitoring Carbonate Chemistry of Surfclam Habitat

2. Date of Project Initiation: March 11, 2021

3. Project Investigators:
Dr. Daphne Munroe
Rutgers University, Haskin Shellfish Research Lab, 6959 Miller Ave., Port Norris, NJ 08349
dmunroe@hsrl.rutgers.edu
856-785-0074

Dr. Jason Morson
Rutgers University, Haskin Shellfish Research Lab, 6959 Miller Ave., Port Norris, NJ 08349
jmorson@hsrl.rutgers.edu
856-785-0074

Dr. Grace Saba
Rutgers University, Department of Marine & Coastal Sciences, 71 Dudley Road, New Brunswick, NJ, 08901
saba@marine.rutgers.edu
848-932-3466

4. NJDEP Project Manager(s): Reneé Reilly (Division of Science & Research, Bureau of Environmental Assessment, renee.reilly@dep.nj.gov) and Colleen Brust (Marine Resources Administration, colleen.brust@dep.nj.gov)

5. Quality Assurance Officer: Lee Lippincott (Division of Science & Research, Bureau of Environmental Assessment, lee.lippincott@dep.nj.gov)

6.

7. Project Description

A. **Objective and Scope Statement**:
The Atlantic surfclam fishery has been identified among the most exposed to offshore wind energy development impacts by the National Oceanic and Atmospheric Administration, National Marine Fisheries Service (Methratta et al., 2020) and the Bureau of Ocean Energy Management (Kirkpatrick et al., 2017). The major New Jersey surfclam fishery port is Atlantic City, which is one of the most valuable in the US in total revenue from this industry. Surfclam fishing vessels are large and use hydraulic dredges (Powell and Mann, 2016; Powell et

al., 2017), limiting their maneuverability to safely navigate in and around windfarms, several of which overlap with active surfclam fishing grounds. This research will provide the information and sampling methodology needed to include a survey of surfclams in any fishery monitoring plan in leases where overlap exists between fishing activity and wind energy development.

A novel sampling dredge has been designed through an industry-science collaborative process (NSF, 2016) that would allow surveying within both lease areas. This research will assess the capture efficiency and size selectivity and compare the dredge performance against the federal survey dredge. Field observations to help quantify the risk of climate change to the stock off New Jersey is limited. This project consists of the following four objectives that will address these needs:

Objective 1: Construction of a novel surfclam dredge, designed by Tom Dameron (Fishing Industry Partner) that can be towed by a smaller commercial fishing vessel (relative to the federal survey vessel) and collect sub-market sized clams. The vessel will stage survey trips out of the commercial docks in Atlantic City.

At this time, no tool exists to conduct clam surveys in areas where commercial fishing grounds and wind energy areas overlap.

Objective 2: Calibration of the dredge so that results are comparable to the federal survey that use commercial hydraulic dredges to demonstrate equivalent sampling capability.

If this novel dredge is to be used to survey within wind lease areas, it is imperative to assess the capture efficiency and size selectivity, and to calibrate the dredge against the federal survey dredge. This information would ensure that the data collected with this tool could be seamlessly integrated with existing, long-term data collected by the federal survey. Three separate experiments will be done to quantify the performance of the novel dredge:

1. A calibration experiment that would allow direct comparison of newly collected survey data from wind farms with long-term federal survey data sets;

2. A depletion-based experiment that would measure capture efficiency; and

3. A selectivity experiment that would estimate the size-selectivity of the dredge.

The data provided from these experiments will allow integration of the data collected with this research dredge design with other survey platforms and allow comparable abundance estimates to be made.

Objective 3: Collection of ocean acidification data to provide information about environmental change that is a factor in surfclam growth and survival. This vertical stratified sampling design will measure depth, conductivity/salinity, temperature, pH, and concentration of carbon dioxide in seawater or $p\mathrm{CO}_2$ (-log[CO_2]). Discrete depth seawater samples will be collected by Niskin bottles for pH, total alkalinity, and dissolved inorganic carbon analysis to confirm pH and $p\mathrm{CO}_2$ sensor-based measurements.

The habitats occupied by surfclam and the surfclam fishery are sensitive to ocean acidification and warming water conditions. Recent research has demonstrated that surfclam are susceptible to both of these environmental stressors (Narváez et al., 2015; Pousse et al., 2020). During the summer, bottom water in the coastal ocean offshore of New Jersey experiences reduced pH and aragonite saturation (Wright-Fairbanks et al., 2020) and upwelling events further reduce pH and aragonite saturation in this area (Poach et al., 2019). Further, NJDEP published the 2020 New Jersey Scientific Report on Climate Change which states, “New Jersey is at increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests, with southern New Jersey counties ranking second in the United States in economic dependence on shelled mollusks.”

It is important to address this data gap by water quality data, including carbonate chemistry, in these bottom water habitats where wind leases may interact with oceanography to alter these conditions. This will be achieved by vertical casts with a suite of sensors for profiles of depth, conductivity/salinity, temperature, pH, and concentration of carbon dioxide in seawater or $p\mathrm{CO}_2$, and the collection of discrete seawater samples via Niskin bottles to determine pH and $p\mathrm{CO}_2$ sensor-based measurements.

Objective 4: Measure surfclam biological response indicators;

- abundance,
- size,
- shell strength, and
- condition index

One of the largest gaps in ocean acidification research, identified by federal and several state agencies and committees, is co-located biological response monitoring (Goldsmith et al., 2019). Co-located measurements of carbonate chemistry and shellfish biology are important for understanding how changing ocean conditions may affect important commercial species like surfclam. Most of what we know about organism response results from single-species laboratory studies and may not capture realistic, natural conditions or variability. Therefore, simultaneous measurements of surfclam biological response indicators (e.g., abundance, size, shell strength, condition index) need to be co-located with carbonate chemistry observations in the field (Objective 3) to observe and predict biological impact in natural conditions. To address this, additional biological data will be collected at the stations occupied for the three calibration experiments. These include Petersen grab samples to assess the abundance and shell condition of recent clam recruits, and clam shell sectioning/aging and analysis of shell thickness and strength.

B. **Data Usage**:

This study will employ the best available scientific methods to support the State's mandate to protect and responsibly manage one of New Jersey's most valuable marine fisheries. The study was developed through a collaboration between Rutgers University, Surfside Seafood Products, NOAA's Northeast Fisheries Science Center, and the New Jersey Department of Environmental Protection in a series of monthly interagency meetings, beginning in April of 2021, and intended to identify research needs for the surfclam industry. Several NJDEP (RMI) objectives are met with this research project (https://www.nj.gov/dep/offshorewind/rmi.html). This is a scientifically rigorous, hypothesis-based, and scientifically defensible research project, and the results will be reproducible and statistically robust. The results of this study will be usable by surfclam fishery managers to identify and inform actions for adaptive management to avoid, minimize, and/or mitigate impacts by providing a method to assess surfclam resources pre- and post-construction.

Specifically, this study will provide quantitative observations of surfclam abundance and population characteristics including length/age frequency, growth rates, condition (meat weight), and shell strength. These data will help inform the status of the stock on fishing grounds occupied by vessels in the New Jersey surfclam fleet. This study will also provide observations of water quality parameters at stations occupied for clam sampling, including temperature, salinity, and carbonate chemistry (pH, pCO_2) profiles. These environmental observations will contribute to the NJDEP database of water quality observations in the coastal ocean. Collectively, the data provided by this study will help the NJDEP understand the interactions and impacts of offshore wind energy projects on state biological (surfclam) and environmental (water quality) resources.

C. **Data Quality Objectives**:

Data generated in Objective 1 falls in Level 1. In this objective, novel sampling gear will be built. No data will be collected during this objective.

Data generated in Objective 2 falls within Levels 2 and 3. The calibration data will serve to develop and support survey methods. In the process of dredge calibration, data will be generated about surfclam stock abundance and population characteristics that will provide information about the conditions of the surfclam stock that is exploited by the commercial fishery in New Jersey.

Data generated in Objective 3 will be used to develop a new sampling method (Level 2) that, if successful, would allow carbonate chemistry profiles to be collected. To our knowledge, this is a novel method that would allow comprehensive and real time carbonate chemistry to be sampled. The measurements themselves would fall in Level 3 because they can be used to help better define the coastal ocean water quality and carbonate conditions.

Data generated in Objective 4 falls spans Levels 2 and 3. New methods will be developed that will allow coincident environmental (carbonate chemistry) and biological (clam condition and shell strength) information to be collected. This objective will also provide data including juvenile recruitment and clam shell strength and age information that can provide information about the status of the surfclam stock and its response to climate change and offshore wind energy development.

D. **Monitoring Network Design and Rationale**:

Location of stations (n=30) occupied for the calibration experiment that will allow direct comparison of the novel dredge with the federal survey will be determined in a randomly stratified design, as designated by the federal survey team. The sampling protocols followed by the federal clam stock assessment survey will be adopted and followed (NEFSC, 2017; 2022). A survey track will be identified such that one vessel will work through the stations in one direction, while the other vessel will work in the opposite direction. This will provide paired catch information for the two survey dredges at the same location at nearly the same time and will ensure that half of the stations will be sampled by one or the other vessel first. Station locations for the depletion and selectivity experiments will be selected based on relative surfclam abundance information from the federal survey calibration such that the five depletion experiments will occur in locations that occupy stations that span the range of observed clam densities. The performance of the dredge is expected to vary slightly as clam abundance changes; therefore, this station selection strategy will allow the data generated in the experiment to have relevance across the range of clam abundances that will be encountered in future surveys. Methods for the NEFSC Bottom Trawl Survey are described in Politis et al. 2014)

E. **Sampling Procedures**: Objective 2

(Clam Dredge Tows):
At each station, the dredge is towed for 5 minutes at 3 knots (tow distance 1.5 nautical miles); however, this time/distance may need to be adjusted to avoid error caused by gear saturation. In the case of gear saturation (a full dredge), the catch will be discarded without sampling and a repeat tow will be performed that is 30 seconds shorter. This will be repeated until the catch fills less than 85% of the dredge volume. On every tow, the location of the dredge at bottom contact will be recorded, and the location at haul back. These positions will delineate the start and stop of dredge sampling. Ship position data during each tow will be continuously recorded as an estimate of the position of the dredge on the bottom. Additionally, sensors attached to the dredge will measure water temperature and estimate bottom contact engagement. Location data will be used to estimate the distance sampled for each tow (swept area). The catch from each tow will be sorted and deposited in bushel baskets so that the volume of the entire clam catch can be measured for each tow. Volumetric subsamples (at least one bushel) of the catch from each tow will be taken and all animals in the bushel subsample will be counted and shell height (the longest axis) measured. The counts from the volumetric subsample will be scaled up using the total catch volume to estimate total number of clams for a given tow. Shell height of all surfclams in the subsample will also be measured using an electronic length board connected to a computer that will record each measurement to the nearest 1 mm in an electronic spreadsheet. A backup non-electronic length board and paper data sheets will be available for use if the electronic board fails. These protocols mirror established protocols used in the NEFSC federal surfclam survey.

Tow protocols and sample processing made in the depletion experiment will follow those outlined above, with the exception that tows will be made repeatedly within a defined area repeatedly until the catch drops below 20% of the initial catch volume. Previous experiments for the federal survey have required 10 to 25 repeat tows to sufficiently reduce the catch to 20%. Tow start, end, and track locations will be recorded as described above for the calibration experiment. The catch for every tow will be measured volumetrically in bushel baskets, and a one-bushel subsample will be taken on every third tow.

Tow protocols and sample processing for the selectivity experiment will follow those outlined above with the exception that three tows (setup tows) will be made using the dredge with open bar spacing (spacing typical of the commercial fishery that will allow clams approximately 120mm shell length and smaller to pass through the dredge). The bar spacing would then be closed down and the station resampled with three additional tows made perpendicular to and crossing the setup tows. Catch for every tow will be measured volumetrically in bushel baskets, and a 1-bushel subsample of the clams will be measured on every tow.

Objective 3 (Water Quality Sampling):
At each station in each calibration experiment vertical casts will be performed (surface to bottom) with a cage fitted with a Sea-Bird SBE-19 CTD, a SBE 18 pH profiling sensor, and a Pro-Oceanus CO2-Pro CV profiler ($p\mathrm{CO_2}$). The remaining carbonate system parameters (including total alkalinity and carbonate saturation states) will be calculated using CO2SYS for MATLAB (v3.0) with temperature, salinity, pressure, pH, and pCO2 as inputs (Lewis & Wallace 1998; Sharp et al. 2020; van Heuven et al. 2011). Quality assurance procedures for each sensor (calibrations, cleaning, and comparability/bias tests) are described in Sections 6 and 8. Quality control procedures are described in Section 9.

At the first and last station for each cruise, discrete seawater samples at select depths will be collected into borosilicate glass bottles, preserved with saturated mercuric chloride, and analyzed for pH, total alkalinity, and dissolved inorganic carbon by Baoshan Chen who operates a carbonate chemistry laboratory at Stony Brook University (see Sections 5F and 5H for sample custody, preservation, and analytical procedures). $p\mathrm{CO_2}$ will be calculated from the discrete samples using CO2SYS with temperature, salinity, pressure, pH, total alkalinity, and dissolved inorganic carbon as inputs. Discrete measured pH and calculated $p\mathrm{CO_2}$ will be compared to sensor-based measurements of pH and $p\mathrm{CO_2}$ for ground truthing (i.e., to determine field accuracy) and to ensure high data quality from the profiling sensors. These data will be used to examine spatial variability in physical water column structure as well as temperature and carbonate chemistry at surfclam collection sites for comparisons to biological/shell metrics (see next section – Objective 4).

Objective 4 (Clam Grab Sampling, Aging, Shell Strength):
At each station, a subsample of surfclams will be retained and used for shell analyses. The subsample of surfclams retained at each station will target a minimum of 30 and maximum of 50 individuals and will be made by randomly selecting clams in proportion to their abundance in each 20mm length bin. Selecting the subsample in proportion to the abundance of size classes produces an unbiased sample age composition (Kimura 1977; Goodyear 1995; Coggins et al., 2013). Clam shells can be broken when the catch is dropped into the hopper; therefore, preference will be made to select surfclams with shells wholly intact. The clams in the subsample will be placed into a bag labelled with the station and sampling

information and stored on ice or frozen if a freezer is available, prior to returning to the lab for processing. At the lab, each subsample will be stored frozen until processing.

Each clam will be thawed in the lab, and measurements of shell length, height and depth will be made, and each empty shell photographed (with scale). Meats will be shucked and dried at 60°F to a constant dry weight in a drying oven. The dried meats will be weighted to the nearest 0.1 g.
Condition factor will be calculated using whole tissue dry weight and shell height (Cameron et al. 2019). Empty shells will be dried with a paper towel and weighed, and each valve labelled with a unique sample identifier that is cross-associated with collection information, station and environmental data, and biological metrics for the sample. Shell strength of the left valve of each clam will be measured using an Instron material-testing machine that measures the load, time, and compression required to fracture the surfclam shell (Burnett & Belk 2018; Wright et al. 2018). Shell thickness to the nearest 0.01mm will be measured on fractured shells at the shell growing edge.

The right valve from each shell will be sectioned, polished and age assessed. Shells will be packed with modeling clay (to prevent breakage) then cut on a tile saw. Cuts will be made from the growing edge through the hinge such that the chondrophore is bisected. The bisected shell will be polished on a griding wheel using progressively finer grit sanding paper and polishing liquid until the chondrophore is polished to a glossy sheen. The polished chondrophore section will be imaged on a calibrated microscope (10x or greater magnification) and the image will be archived with file naming convention following the unique sample identifier. Ages of surfclams can be reliably determined from annular rings laid down in the shell (Jones et al., 1978). Age of each chondrophore section will be evaluated by a reader by counting these annular rings in the microscope images. Each reader will be trained with a standard image set and their counting accuracy evaluated using a separate testing image set. Only readers who test at 85% or greater counting accuracy, and who do not over or underestimate ages in the test set by >4 years will be used to count chondrophore images.

One sediment grab sample will be collected at each station. The grab samples will be used to collect recent (1- to 2-year-old) clam recruits, and evaluate the buffering capacity (the volume of shell hash) in the upper sediment layer. A Petersen grab sampler will be deployed over the side of the vessel to collect a 0.1m^2 bottom sediment sample. The sample will be placed on a sieve table with 1.0 mm stainless steel mesh and washed through the screen with the deck hose. All benthic meiofauna (including clams) and any shell hash material will be retained on the sieve will be placed in a bag labelled with the station number and date and stored on ice or frozen (if freezer capacity is available on board). Samples will be returned to the laboratory and stored frozen until processing. To process, each sample will be thawed and meiofauna will be sorted, identified, and all surfclams will be measured. All shell hash fragments in the sample will be isolated, dried, photographed in a single layer with scale and weighed in bulk to the nearest 0.1g.

F. **Sample Custody Procedures**:

All clam and sediment samples retained at each station that will be returned to the lab will be logged into a master record upon collection and storage. The master record will note the unique sample name as labelled on the bag, number of bags for the sample, the date, time, and station where the collection was made, the method of preservation (on ice or in freezer), and name of the technician who made the collection and storage. At the end of the cruise, this master sample log will be used to check every sample that is offloaded into coolers with ice packs for transport to the lab against the master log to ensure all samples are recovered from storage holds on the vessel. This log will then be used to confirm receipt of each sample at the lab and to note what freezer is being used to store each sample. The master sample log will be updated with a record of the name of the technician and date of sample processing when each sample is processed.

Discrete seawater samples preserved for pH, total alkalinity, and dissolved inorganic carbon analysis will be placed in a cooler with ice for transport to PI Saba's Rutgers laboratory. Once there, they will be stored at 4˚C temporarily until shipment to the analytical lab (Stony Brook University). Sample documentation for discrete seawater samples will follow the procedures described for clam and sediment samples in the previous paragraph.

G. **Monitoring Sites and Frequency of Sample Collection**:

The sites occupied in this project are not yet identified and will be selected at random. All will be located on the continental shelf off New Jersey, in federal waters on sandy bottom. The total number of stations sampled in this project will be approximately 40 (the final number will depend on time available for additional depletion and selectivity experiments on those trips). At each station, a hydraulic dredge sample will be taken, a sediment grab sample will be taken, and a water chemistry profile will be made. On the first and last station of each cruise, a discrete water samples will be collected at target depths for carbonate chemistry analysis.

H. **Analytical Procedures**

Analytical procedures used for sampling clams from the hydraulic dredge tows include shell length measurements (these will be made with a length board or calipers), and mass (measured with a balance). For each tow, 1 bushel of clams will be measured which represents between 80 to 200 clams depending on the length frequency of the sample. These will be processed upon collection (no holding time). Shell ages will be analyzed by visual inspection of sectioned and processed hinges. Shell breakage strength will be measured with a materials-testing machine. Between 30 to 50 individual clams will be measured for age and breakage strength per station and holding time in freezers prior to analysis will not exceed 6 months.

Discrete seawater samples will be analyzed for pH spectrophotometrically using purified meta-Cresol Purple dye (Clayton & Byrne 1993; Liu et al. 2011), total alkalinity via open cell Gran titration (Cai et al., 2010; Chen et al., 2015; Huang et al., 2012), and dissolved inorganic carbon using a nondispersive infrared method (Chen et al., 2015; Huang et al., 2012) (Table 1). Samples will be analyzed by Baoshan Chen who operates a carbonate chemistry laboratory at Stony Brook University. This lab uses community-accepted quality control protocols (Dickson et al. 2007) and certified reference materials (CRMs; for testing accuracy of total alkalinity and dissolved inorganic carbon measurements) and Tris buffers (for testing accuracy of pH measurements) obtained from Andrew Dickson at UCSD Scripps Institute of Oceanography). This lab has also participated in a blind calibration inter-laboratory comparison procedure, in collaboration with Andrew Dickson's lab, to ensure high analytical accuracy and precision.

Table 1

Parameter	Number of samples*	Sample Matrix	Analytical Method	Sample Preservation	Holding Time
pH	12 samples in duplicate	seawater	spectrophotometric	Saturated mercuric chloride (0.02%)	< 2 months
Total alkalinity	12 samples in duplicate	seawater	open cell Gran titration	Saturated mercuric chloride (0.02%)	< 2 months
Dissolved inorganic carbon	12 samples in duplicate	seawater	Nondispersive infrared method	Saturated mercuric chloride (0.02%)	< 2 months

*Per field effort/cruise

7. Data Quality Requirements

Detection limits do not apply to biological data collection such as catch volume, shell lengths, ages, and strength, dry tissue mass, and meiofauna abundance.

Sensor quality assurance and data quality control will be conducted and documented. These techniques will be followed based on the scientific literature and manufacturer recommendations. Quality assurance procedures for each sensor include calibrations, regular sensor cleaning, and comparability/bias tests (Tables 2 and 3). The CTD, pH, and

pCO$_2$ sensors will be calibrated by the factory annually. This is in accordance with recommended annual factory calibrations from the manufacturer. The pH sensor will also undergo a factory recommended in-house calibration at the start of every field effort/cruise, and then at least once per month. Following each field effort/cruise, the CTD, pH, and pCO$_2$ sensors will be cleaned.

In addition to annual factory calibrations, comparability and bias testing will be conducted (Table 3). These procedures as followed are outlined in the manual drafted by the manufacturers and will be used to confirm the factory calibration. The CTD will be referenced to a second, factory calibrated SBE-19 CTD in a seawater tank before and after each deployment. The depth-specific pH and pCO$_2$ sensor data at sites where discrete water samples are collected (at first and last stations of each field effort/cruise) will be compared to those discrete pH measurements and pCO$_2$ calculations. If any values are found out of the acceptable range reported by the component manufacturers ('Comparability or Accuracy' range listed in Table 2), the sensors will be recalibrated.

Table 2

	CTD	**pH**	***p*****CO$_2$**
Comparability or Accuracy *based on manufacturer claims*	Temp.: ±0.005 °C Cond.: ±0.0005 S/m Pres: ±0.1dbar	±0.1	Conc: ±0.5%
Resolution *based on manufacturer claims*	Temp.: ±0.0001 °C Cond.: ±0.00005 S/m Pres.: ±0.03 dbar	±0.005	Conc.: ±0.01 ppm
Bias	Bias will be determined through the direct comparisons with simultaneous tank tests with another factory calibrated SBE-19 CTD.	Bias will be determined through a three-point calibration test before each deployment/field effort/cruise as well as comparison to pH of discrete seawater samples.	Bias will be determined through comparison to pCO$_2$ of discrete seawater samples.

Table 3

Analyte	**DQI**	**Field QC Check**	**Frequency of Collection**	**Acceptance Criteria**	**Corrective Actions**
CTD	Comparability and bias	In tank CTD comparison	Before and after each field effort/cruise	Within 'Comparability or Accuracy' range listed in Table 2	Suspect values are flagged as described in Section 9 of this document.
CTD	All	Manufacturer Factory Calibration and cleaning	Annually	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2

pH	Comparability and bias	Discrete seawater sample collection	At first and last station of each field effort/cruise	Within 'Comparability or Accuracy' range listed in Table 2	Suspect values are flagged as described in Section 9 of this document.
pH	All	In-house sensor calibration	At the start of every field effort/cruise, and then at least once per month (factory recommended)	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2
pH	All	Manufacturer Factory Calibration and cleaning	Annually	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2
$p\mathrm{CO}_2$	Comparability and bias	Discrete seawater sample collection	At first and last station of each field effort/cruise	Within 'Comparability or Accuracy' range listed in Table 2	Suspect values are flagged as described in Section 9 of this document.
$p\mathrm{CO}_2$	All	Manufacturer Factory Calibration and cleaning	Annually	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2

8. Data Quality Assessments

A. Data Representativeness:

Station density for dredge tows follows the standards used by the federal stock assessment survey (Politis et al. 2014). Over time, data collected on the federal survey has a coefficient of variation of 0.25. Given that we are following the same protocols and will use the same station density, we anticipate the same level of precision and accuracy for this project in determining the characteristics of the surfclam population.

B. Data Comparability:

These biological samples are being collected following the same protocols and using the same stations as the federal surfclam stock assessment survey. The results of this study will be directly comparable to the federal survey timeseries. Likewise, state (New Jersey and New York) surfclam surveys also follow the same sampling protocols and the data collected in this project will be directly comparable to those survey timeseries. Further, other industry-funded projects have employed these same protocols and the data collected in this project will be able to be directly compared to those studies.

A major difference in the data collected in this project is the addition of environmental and water quality (particularly carbonate chemistry) data that can be related to the biological data collected at each station. There is limited carbonate chemistry data in the coastal Mid-Atlantic, but a recent glider-based ocean acidification monitoring program led by PI Saba has been measuring vertically-resolved seasonal pH (and estimating total alkalinity, $p\mathrm{CO}_2$, aragonite saturation state) in coastal shelf waters of New Jersey for the past 2-3 years (e.g., Wright-Fairbanks et al. 2020). Therefore, carbonate chemistry data collected in this study can be compared to those seasonal glider-based data. Additionally, this pH glider will continue to be deployed seasonally near the sampling area for this study, thus allowing for direct comparisons between glider-based observations and the pH and $p\mathrm{CO}_2$ measurements collected in this study. However, it should be noted that this dynamic coastal region is subject to high spatial, seasonal, and interannual variability. Therefore, large differences in pH and $p\mathrm{CO}_2$ between data collected in this study and historical data (from previous years) or data collected from the pH glider in a different location at the same time could be observed.

9. **Calibration Procedures and Preventive Maintenance**:

The dredge sampling objectives in this study are primarily a gear calibration procedure. The hydraulic dredge being used in this and future studies, has yet to be calibrated. These kinds of calibrations require expensive vessel and staff time and in many cases are not done. In this case, we are performing these calibrations at the outset to provide important information that allows the biological data collected by this dredge to be standardized and to improve the ability to compare these data to other surveys and projects.

The digital length boards are calibrated at the beginning of each cruise using known length standards. The balances used are calibrated every 6 months using known mass standards. The materials strength testing unit will be factory calibrated at the beginning of this program.

As mentioned in Section 6, the CTD, pH, and $p\mathrm{CO}_2$ sensors will be calibrated by the factory annually. This is in accordance with recommended annual factory calibrations from the manufacturer. The pH sensor will also undergo a factory recommended in-house calibration at the start of every field effort/cruise, and then at least once per month.

10. **Quality Control Checks**:

Quality controls do not apply to biological data collection such as catch volume, shell lengths, ages, and strength, dry tissue mass, and meiofauna abundance. Shell age counts will be quality control checked by having a subset (5%) of all ages to be checked by an independent reader. If the quality control check shows disagreement in ages of more than 10% of the re-aged samples, a second reader will evaluate the entire age image set and the agreement among all readers will be evaluated.

Quality control procedures for data produced from the CTD, pH, and $p\mathrm{CO}_2$ sensors entail evaluations of sensor field accuracy (Tables 2 and 3). Suspect values outside of the field accuracy range will be flagged. Following each deployment, the final quality-controlled data will be within the 'Comparability or Accuracy' range listed in Table 2 of this document. If a value is found outside these criteria, it will be flagged in the final dataset. Each data point will be treated independently so that any one point flagged will not restrict use of the other quality data from the same deployment.

11. Documentation, Data Reduction, and Reporting

A. Documentation:

On the cruises, a master log of all samples collected will be maintained on a physical data sheet (printed on waterproof paper). All biological data collected on the vessel (shell lengths, catch volumes, station location, tow duration) will be recorded on a digital spreadsheet on board. All digital data files will be backed up on an external drive at the end of each watch. Backup physical datasheets will be carried in the event that there are problems with the computer or spreadsheet while on the cruise. All science crew will have a waterproof notebook in which they will record observations made during their watch.

After field efforts are complete, all data files related to this project will be archived in a folder on a server at the Rutgers Haskin Shellfish Research Lab, and will be backed up on a cloud server. Any physical data records (sample master log, notebooks, data sheets) will be held on site at Rutgers Haskin Shellfish Research Lab, and will be scanned as a backup and the data entered into digital databases.

B. Data Reduction and Reporting:

Data from the project will be assembled and organized into summary files that contain trip and tow level station, biological, and water quality data. These summary data files will be provided directly to the NJDEP in .csv file format. Summary reports will also be generated describing the summarized biological and water quality data in the form of figures and maps.

12. Data Validation:

All data will be quality control checked by independent technical staff. Individual observations will be plotted to evaluate data spread, data coverage, and to identify possible outliers. Pivot tables will be used to similarly visualize data spread and identify possible outliers or data entry errors. For any outlier identified, raw data sheets will be consulted to verify whether these are true outliers, or if they represent an entry error. If it is an entry error, the data will be corrected. If the observation represents a true outlier, statistics will be performed on the dataset with the outlier removed, and with the outlier included. Both will be reported to the NJDEP for clarity.

Data validation and quality control procedures for pH and $p\mathrm{CO}_2$ data are described in above Sections 6 and 9.

13. **Performance and Systems Audits**:

Project performance will be monitored by the lead researchers (Munroe and Saba). After each cruise, the sample collections realized relative to the cruise goals will be assessed. If the sample collection on a given cruise was >20% lower than expected, the researchers will notify NJDEP Project Managers to inform them and to discuss options for mitigation. Sample processing and analysis in the lab will be monitored by monthly consultation of the sample master log data sheet to ensure that consistent progress is being made on sample processing in the lab over time. Should the project leads identify a gap in sample processing, a project team meeting will be called to identify why this gap occurred and how quickly processing can resume. Project leads will also regularly review data sheets and complete data validation to assess data quality. If the project leads identify a data quality issue, a project team meeting will be held to identify the source of the problem and how it might be corrected. Technical staff responsible for each step in the sample collection, retrieval and processing chain will be identified on the master sample log. If data quality or sample processing issues identified are consistently associated with a single individual, that individual will be assigned to other tasks and removed from the project.

14. **Project Operations and Responsibility:**

Sampling operations: Daphne Munroe, Grace Saba, Jason Morson, Nicole Waite, Ailey Sheehan, Jenn Gius, Joey O'Brien, Hails Tanaka, Sophia Piper
Sampling QC: Daphne Munroe, Grace Saba, Jason Morson, Nicole Waite, Ailey Sheehan, Jenn Gius, Joey O'Brien, Hails Tanaka, Sophia Piper
Laboratory analysis: Nicole Waite, Ailey Sheehan, Jenn Gius, Joey O'Brien, Hails Tanaka, Sophia Piper
Laboratory QC: Nicole Waite, Ailey Sheehan, Jenn Gius, Joey O'Brien, Hails Tanaka, Sophia Piper
Data processing activities: Nicole Waite, Ailey Sheehan, Hails Tanaka, Sophia Piper
Data processing QC: Nicole Waite, Ailey Sheehan, Jenn Gius, Joey O'Brien, Hails Tanaka, Sophia Piper
Data quality review: Daphne Munroe, Grace Saba, Jason Morson, Nicole Waite, Ailey Sheehan
Performance evaluation/auditing: Daphne Munroe, Grace Saba, Jason Morson
Overall QA: Daphne Munroe, Grace Saba, Jason Morson
Principal investigator: Daphne Munroe

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Introduction

Among managers, scientists, and community members, there is concern regarding the impact of ongoing ocean acidification on marine life. Ocean acidification is thought to pose particularly strong threats to sedentary, calcifying organisms, such as bivalves (Byrne & Fitzer, 2019; Johnson, 2021). Most studies investigating the organismal impacts of ocean acidification have been conducted in the laboratory and may not accurately capture the variation in conditions and responses that occur in the environment. The Atlantic surfclam is an ecologically and economically important bivalve throughout the Mid-Atlantic Bight. This study sought to evaluate the relationship between existing carbonate chemistry (pCO_2, pH, Ω_{Arag}) variation across locations in the field and surfclam shell strength to evaluate how sensitive the species may be to continued ocean acidification. The majority of the details of this study were described in a previously issued report (Munroe et al., 2024). This report describes the final analysis undertaken with the data, particularly regarding the impact of animal age on shell strength.

Methods

All methods for biological and oceanographic sample and data collection are described in the initial report. Prior to additional analysis, the environmental data was quality checked again in line with the procedure described in the initial report to increase confidence that sensors were below the thermocline for a sufficient amount of time to collect accurate near-bottom readings.

For the additional regression analysis, a linear mixed effects model was constructed to investigate the relationship between carbonate chemistry, age, and weight-standardized shell strength in clams from retained stations. Ω_{Arag} and log-transformed age were treated as fixed effects, while survey station was treated as a random effect.

Results

After environmental data from all stations was reviewed again to ensure confidence in sensor readings, data from 18 stations were retained for analysis (see Fig. 1).

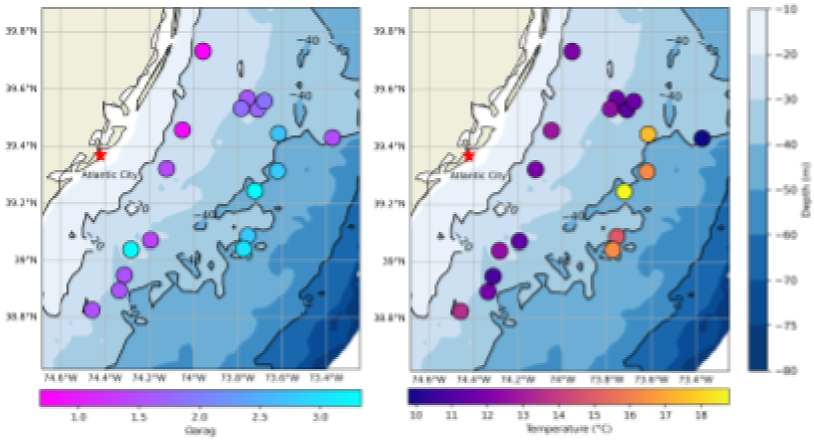

Fig. 1: Mean bottom Ω_{Arag} and temperature observed at 18 retained survey stations.

In line with previous analysis, Ω_{Arag} was not found to be a strong predictor of standardized shell strength in this model framework (est. = 5.89×10^{-5}, SE = 6.69×10^{-5}, 95% CI [-7.17×10^{-5}, 1.89×10^{-4}], $t = 0.880$) (see Fig. 2A). Log-transformed age was found to be a significant, negative predictor of standardized shell strength (see Fig. 2B), but the magnitude of the effect was small (est. = -2.54×10^{-4}, SE = 4.29×10^{-5}, 95% CI [-3.37×10^{-4}, -1.70×10^{-4}], $t = -5.92$). Overall, none of the recorded oceanographic variables were found to vary significantly with standardized shell strength across any evaluated model.

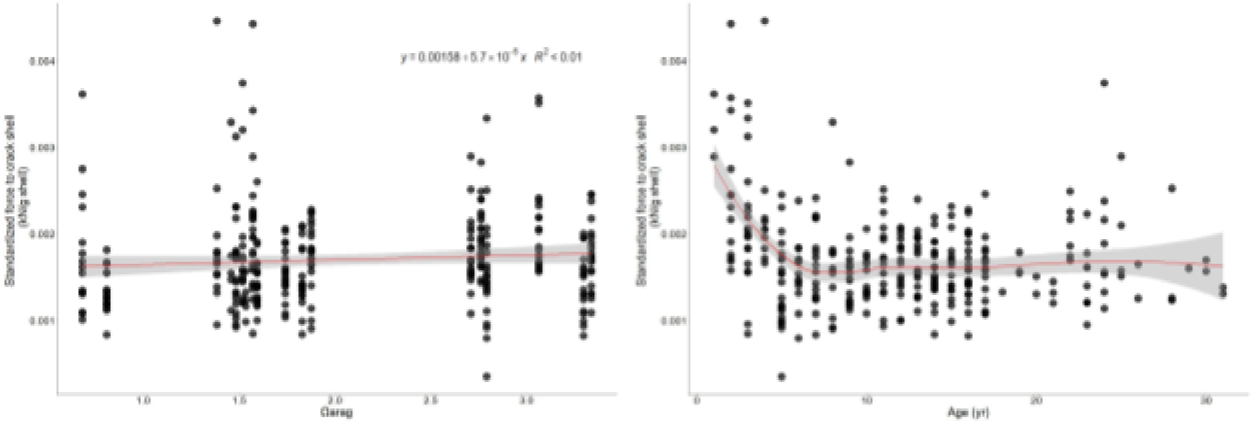

Fig. 2: Standardized force to crack shell of n = 331 retained surfclams displayed by (A) Ω_{Arag} and (B) animal age. In (A), equation is that of simple linear regression displayed.

Discussion

Consistent with the findings of the initial report, the analysis described here did not find an association between Ω_{Arag} and shell strength in surfclams. Across retained survey stations, Ω_{Arag} varied from 0.68 to 3.34, a range which includes values that were found to be stressful to bivalves in the laboratory (Leung et al., 2022). This may indicate that surfclam shells may not be sensitive to the levels of carbonate chemistry variation present in their natural environment. Of note, surfclams live as meiofauna within low pH sediment porewater, so it is reasonable to consider that surfclams may be resilient to relatively acidic conditions. However, overall, the fact that the environmental data collected here consisted of single, water column point measurements means the results should be interpreted with caution. Future studies should aim to collect longer-term data on carbonate chemistry variation in the field.

Age was found to modulate standardized shell strength, with clams younger than about 6 years of age exhibiting stronger shells compared to older animals. While log-transformed age was found to be a significant predictor of shell strength in our model, including age as a variable did not greatly increase the explanatory power of the model or alter the discernable relationship between the other environmental variables and shell strength. All animals analyzed in this study were collected using a commercial clam dredge, which was ideal for collecting large, adult surfclams over a large study area. However, this method was not focused on collecting young adult clams aged 1-5 years, those which showed the most variation in strength. Future studies on surfclams should consider this potential sampling gap, with future shell strength studies focusing on younger aged clams in particular.

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