Estuary-Dependent Growth Differences in Farmed Northern Quahog (Mercenaria mercenaria) in New Jersey, with Implications for the Aquaculture Industry

Authors: Gordon, Zachary, Sutherland, Sandy, Shoemaker, Katyanne M., Rodenbush, Colleen, and Robillard, Eric

Source: Journal of Shellfish Research, 44(3) : 377-385

Published By: National Shellfisheries Association

URL: https://doi.org/10.2983/035.044.0305

Journal of Shellfish Research, Vol. 44, No. 3, 377–385, 2025.

ESTUARY-DEPENDENT GROWTH DIFFERENCES IN FARMED NORTHERN QUAHOG (*MERCENARIA MERCENARIA*) IN NEW JERSEY, WITH IMPLICATIONS FOR THE AQUACULTURE INDUSTRY

ZACHARY GORDON,[1]* SANDY SUTHERLAND,[2] KATYANNE M. SHOEMAKER,[3] COLLEEN RODENBUSH[4] AND ERIC ROBILLARD[2]

[1]*University of Connecticut, CT Sea Grant, 1080 Shennecossett Road, Groton, CT 06340;* [2]*Fishery Biology Program, Northeast Fisheries Science Center, NOAA Fisheries, 166 Water St., Woods Hole, MA 02543;* [3]*Milford Laboratory, Northeast Fisheries Science Center, NOAA Fisheries, 212 Rogers Ave, Milford, CT 06460,* [4]*Fisheries Monitoring and Research Division, Northeast Fisheries Science Center, NOAA Fisheries, 25 Bernard Saint Jean Drive, East Falmouth, MA 02536*

ABSTRACT The northern quahog (hard clam), *Mercenaria mercenaria*, is an economically important shellfish species in New Jersey, yet farmers in some parts of the state recently have experienced reduced growth in cultivated clams. To identify possible reasons for this slowed growth, clams from two farms were compared, where one farm had been experiencing reduced growth and the other had not observed changes. Growth differences were examined between the two areas, both within a single season and as shown by yearly marks on shells collected at both sites. Clam condition was also measured across the growing season, as well as environmental conditions (bottom temperature and current speed) at each site. Clams in the unaffected area reached market size 1 y earlier than those in the area with reduced growth. Analysis of yearly rings showed that growth at the unaffected farm was also higher than in wild clams near either farm, implying that husbandry practices may contribute to enhanced growth. This was supported by clam growth measurements at standardized stocking density on both farms, which showed a smaller but still significant difference in seasonal growth between farms. Bottom water temperature was not different between sites, but current speed differed seasonally. Other important factors affecting growth may include food availability and carrying capacity. The data show that overstocking most likely contributes to the reduced growth. It is hoped that this information can help farmers make informed decisions about farm management when growth issues are observed.

KEY WORDS: Northern quahog (*Mercenaria mercenaria*), hard clam, growth, aquaculture, environment, New Jersey

INTRODUCTION

The northern quahog [*Mercenaria mercenaria* (Linné)], known commercially in the mid-Atlantic region as the hard clam, is one of the top three molluscan aquaculture products in the United States and is grown exclusively on the North American East Coast from Massachusetts to Florida (Yang et al. 2016). It is one of the two main shellfish species cultivated in New Jersey, alongside the eastern oyster, *Crassostrea virginica*. The most recent outlook report (Calvo 2017) estimated that approximately 7.78 million clams were sold for a farm gate value (the average price received by the farm) of at least $1.5 million USD.

Farmers have recently reported to state biologists at the New Jersey Department of Environmental Protection that, in some estuaries, hard clam growth on established leases has declined noticeably over the past 7 y. Similar observations have been made by ReClam the Bay, a nongovernmental organization operating hard clam upwellers in Barnegat Bay, NJ.

Prior investigations into the cause of the declines have led to some general observations. First, some growers independently obtained pathology screenings of their product, but no definitive disease diagnosis was found. Growers also tried varying the genetics of clams seeded on their farm, but continued to experience poor growth. Growers have also noted that oysters and scallops farmed in the same areas did not demonstrate a reduction in growth. After an especially poor season in 2022, when a major clam die-off occurred, there was an increased level of interest from growers in New Jersey, especially the New Jersey Shellfisheries Council, to further understand this poor growth and its spatial extent.

Wild populations of hard clams have also been declining near the farms experiencing poor growth, according to the most recent reports (Bricelj et al. 2017). This supports a hypothesis that environmental factors have changed over time, affecting growth in both aquaculture and wild stocks.

Hard clams are filter feeders, known to feed on a wide variety of items including phytoplankton, resuspended sediments, detritus, and other particulate organic matter (Grizzle et al. 2001). One hypothesis for why hard clams are growing poorly, but oyster and scallop growth has not changed, is a possible energy imbalance between increasing metabolic demands and declining food availability. Preliminary data from New Jersey Department of Environmental Protection's continuous sampling of chlorophyll (Chl-*a*, an indicator of phytoplankton presence) has shown declines in chlorophyll concentrations in the same areas where the decrease in growth has been reported. Hard clams appear to require a greater food supply than other species: Research at the Milford Laboratory has shown a feeding conversion efficiency of 2% for hard clams, 25% for oysters, and 20% for scallops (G. Wikfors 2022 personal communication, NOAA Milford Laboratory) and Galimany et al. (2017) showed that clams are less efficient feeders than oysters, as they have a lower ability to reject excess inorganic matter and are more susceptible to changes in environmental conditions.

It is possible that the affected clams are facing environmental conditions that increase metabolic demand, such as increasing bottom water temperature or changing salinity. Also, some of

*Corresponding author. E-mail: Zachary.gordon@uconn.edu
DOI: 10.2983/035.044.0305

the most important factors that determine food availability for hard clams are primary production (Chl-*a*) and tidal currents. Grizzle and Lutz (1989) determined that the seston flux rate (the current speed multiplied by the seston concentration) was an important indicator of growth. This means that a reduction in current may limit the replenishment of food for the clams. Changing environmental conditions, along with lower feeding efficiencies, may explain why clam growth has slowed whereas other bivalve growth in the same area has not.

The goal of this study was to understand the timing, magnitude, and potential causes of declining the growth of cultured hard clams using condition index (CI) measurements, shell growth measurements, and environmental data. This study was designed as a quick, low-budget investigation to inform farmers on potential reasons why the clam growth has declined.

Although food availability is a key factor for farmed clams, measuring food metrics can be difficult and expensive. Rapid fluctuation of phytoplankton population density in estuarine environments necessitates taking measurements at least weekly to understand food availability over an entire growing season. Also, because clams have a variety of sources of food, measuring only one metric will not show the full picture. For example, Chl-*a*, a commonly used metric for food, is a poor proxy for food quantity and quality for clams because it varies on a scale of hours and does not factor in other sources of food such as detritus, resuspended sediments, or particulate organic matter. In an estuary in New York, ambient Chl-*a* concentration showed no clear relationship with growth of juvenile hard clams (Bricelj 2009).

The present study was designed to provide evidence about the severity of the lower growth observed in the study areas, and explore possible causes, in the absence of food data. The results of the study are intended to provide farmers with tools to make informed decisions on future farm use, identify more focused studies needed, and consider what, if anything, might be done to reverse the trend.

This study compared two historically productive aquaculture sites in New Jersey to evaluate seasonal and long-term hard clam growth trends, as well as local water conditions. One site was an aquaculture lease near Little Egg Harbor Inlet in Barnegat Bay, NJ, where the farmers grow hard clams, oysters, and scallops in aquaculture gear. Since 2015, farmers in this region have observed significant declines in hard clam growth and survivorship. The second site was an aquaculture lease that grows exclusively hard clams further to the south in Great Sound, a separate estuary in New Jersey. The southern farm has maintained consistent productivity and growth. By assessing growth patterns and water conditions between the sites, the aim was to gain a better understanding of how aquacultured hard clams respond to environmental changes and what conditions are most influential to their survival and growth.

The study had three main objectives:

Objective 1: Comparing growth rates and periods of slow growth during the annual production season, using individual clam growth and CI as an indicator of metabolic energy balance. Data were compared between sites to describe timing and magnitude of changes in growth.

Objective 2: Analyzing yearly marks in shells to describe long-term patterns in hard clam growth, by comparing within and between growing sites and between aquacultured and wild clams in both areas.

Objective 3: Identifying changes in seasonal and long-term trends in environmental variables and assessing the sensitivity of hard clam growth and survival to conditions, to provide insight on regionally observed declines in clam production.

MATERIAS AND METHODS

Sampling Locations

Clams were collected from aquaculture farms in Little Egg Harbor, Barnegat Bay, NJ (North Farm) and Great Sound, NJ (South Farm) (Fig. 1), as well as beds of wild clams near each farm. North Farm has observed a decline in growth, whereas South Farm has not reported any change in growth.

Growth and CI

To assess overall clam health throughout the production season, 30 clams were sampled from each farm site each month between March and December 2023. Although the clams at each farm originated from different hatcheries and genetic strains, they were selected from clams that were originally spawned in 2021. Sampled clams were shipped on ice overnight by the partner farmers to the Northeast Fisheries Science Center in Milford, CT for examination.

After arrival at the laboratory, the clams were scrubbed, and shell length measurements (mm) were taken. If further analysis could not be started immediately, the clams were frozen at −20°C until the analysis could be begun.

The soft tissue and valves were separated and dehydrated independently in an Isotemp gravity oven (Thermo Scientific, Pittsburgh, PA) at 60°C. Clams were initially dried for 24 h, and then weights were measured every 12 h to determine the total drying time necessary for weights to stabilize to within 0.01 g between each weighing. For the first set of samples, it was determined that clam tissue and shells were fully dry after 48 h in the oven. Therefore, the subsequent samples were dried for 48 h.

Figure 1. Map of sampling locations. Red circles show location of each farm: North Farm is in Little Egg Harbor (LEH), and South Farm is in Great Sound (GS). (Base map from NJ Aquaculture Siting Information Tool https://njaquaculture.rutgers.edu/.)

TABLE 1.

Samples analyzed for annual growth.

Collection	Location	Date	Number measured	Age (y)	Mean shell length (mm)	Comments
S–Age 2	South Farm, Great Bay	April 2023	23	2	38.4	
N–Age 2	North Farm, Little Egg Harbor	April and June 2023	44	2	24.6	Many broken
N–Age 3	North Farm, Little Egg Harbor	April–October 2022	116	3	42.1	8 collection dates combined
S–Wild	Great Sound	August 2023	51	9–21	85.8	Wild samples
N–Wild	Little Egg Harbor	July 2023	25	9–21	89.8	Wild samples
N–2022	North Farm, Little Egg Harbor	June 2022	12	6–14	92.1	Large clams
N–2023	North Farm, Little Egg Harbor	March 2023	36	6–21	89.9	Large clams

Known-age samples are shown in bold.

Condition index is a widely used indicator of energetic status (Lucas & Beninger 1985). A common calculation for CI in bivalves (including hard clams) is the formula (Zeng & Yang 2020):

$$\frac{\text{soft tissue dry weight (g)} \times 100}{\text{dry shell weight (g)}} \quad (1)$$

This CI was calculated for each individual clam. Paired two-tailed t-tests were performed to compare CI for the two farms for each collection month.

The relationship between soft tissue dry weight and shell length was compared between sites with a Chow test to determine if the data could be described with a single linear model. Shell lengths from monthly samples were also used to track growth over time, based upon average weekly growth rates. These growth rates were compared across farms and compared with the individual growth experiment (below) to understand how stocking density may affect growth.

Individual Growth Experiment

To directly assess clam growth over the growing season, and to control for stocking density differences between farms, three sets of 35 clams each were planted at each farm in 2023. These clams were placed in 0.093 m^2 plastic boxes that were buried in the sediment at each farm. The clams were individually labeled with three colors of nail polish, allowing clam growth to be tracked at the individual level. The boxes were covered with mesh to protect from predators and managed in a manner similar to the rest of the clams on each farm. Individual clam length (mm) was measured three times: at out-planting (March), in the middle of the growing season (July), and at box removal (December). Two-tailed t-tests were used to compare growth rates between farms for March–July and July–December.

Age and Growth Analysis

To assess longer term growth trends, samples were collected between April 2022 and August 2023 from both farms and uncultivated sites near each farm (Table 1). In April–October 2022, known-age clams (originally spawned in 2019) and large clams of unknown age were collected from the North Farm. In the spring of 2023, known-age clams (originally spawned in 2021) were collected from both farms, as well as large clams from the North Farm. Large, wild clams were collected from near both farms in the summer of 2023. The large clams had shell lengths greater than 60 cm and were assumed to be approximately 10 y old. The soft tissue was shucked from the clams, and the shells were cleaned and air dried.

The clean, dry valves were shipped to the Northeast Fisheries Science Center in Woods Hole, MA for age and growth measurement. Once there, the hinge of the left valve was cut in half (Fig. 2A), with the method varying by shell size (Table 2). Most clams were cut using a Buehler Isomet saw (model 11-1280-160; Buehler Ltd., Lake Bluff, IL); the largest samples were cut on a Ridgid tile saw (model R40312; One World Technologies, Anderson, SC). The saw blade was positioned between the edge and the first set of teeth and diagonally across the beak of the umbo. The resulting halves were polished with 320-grit sandpaper at 400 rpm on a Crystal Matter polisher (model 50-503; Crystalite Corporations, Marina Del Rey, CA).

The hinge area of each cut valve was then digitally photographed at 7–30× magnification with an Infinity 8 digital camera (Model I8-LC00-08M; Teledyne Lumenera, Ottawa, Ontario, Canada) and Infinity Analyze software (Version 7.1.1.66; Teledyne Lumenera). These images were used to measure the distance between annuli using ImageJ (version1.49v; Schneider et al. 2012) and the ObjectJ plugin (version 1.03s;

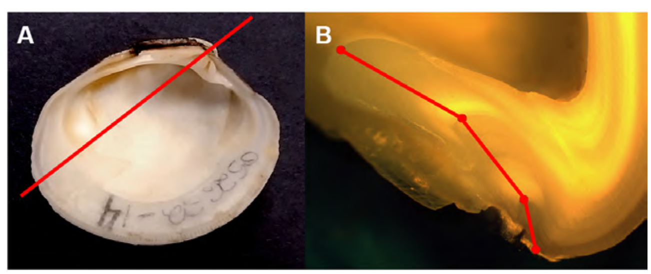

Figure 2. Methods for cutting and measuring clams: (A) The left valve of each clam was cut along the red line and (B) example of line segments drawn to measure growth increments in the hinge.

TABLE 2.

The equipment used for cutting the valves was based on shell size.

Shell width (mm)	Cutting method
<30	Ground down with polisher
30–60	Isomet saw
>60	Tile saw

University of Amsterdam, available from https://sils.fnwi.uva.nl/bcb/objectj).

Identification of annuli followed published protocols for age estimation (Peterson et al. 1983, 1985, Jones et al. 1990, Ridgway et al. 2011). In ImageJ, a line segment was drawn from the origin to the first annulus, another from the first to the second annulus, *etc.*, out to the edge of the hinge (Fig. 2B). This way, an age was determined (the number of line segments) as well as the distance (in mm) between each annulus.

The known-age samples collected in 2022 (3 y old) and 2023 (2 y old) were important in this analysis. The growth analysis only considered the first 3 y, calculated as the additive length of the first three line segments, because the first 3 y are considered to be most important for aquacultured clams. Similarly, two line segments were used to compare growth for the 2-y-old samples. The data were grouped by sampling year and location for further analysis. Two-tailed *t*-tests were used to test for differences between sets of samples.

Environmental Variables

Temperature data loggers (Onset HOBO water temp Pro v2) and shallow water current tiltmeters (Lowell TCM-4) were deployed at both farms from March to December 2023. The temperature loggers were placed just above the sediment surface to measure temperatures comparable to those drawn into the mantle cavity by the clams. Tiltmeters were attached by braided line to a cinder block (Fig. 3) and deployed at each site to continuously monitor current speed. Environmental data were used to assess the relationship of hard clam growth to each variable.

Figure 3. Tiltmeter setup for deployment at each farm site.

RESULTS

Growth and CI

Shell length and dry tissue weight in the monthly samples were different between sites (Fig. 4, Chow test: $P < 0.0001$). Dry tissue weight from the North Farm was 0.0–0.4 g; whereas at the South Farm, it was 0.1–1.6 g. Growth at the North Farm averaged 5 mm over the season and averaged 15 mm at the South Farm. The average weekly growth rate at the North Farm was 0.114 mm March–July and 0.153 mm July–December, compared with 0.395 mm March–July and 0.389 mm July–December at the South Farm.

Condition index (Fig. 5) peaked at both sites in the early spring months and dropped in the early summer, when clams normally spawn. Condition index increased again after spawning before the second smaller drop (presumed spawning event) in late summer and then it continued to increase until the end of the study period at both sites.

Although CI followed a similar pattern at both sites, there were notable differences. Clams at the North Farm spent a larger portion of energy spawning as evidenced by the steep decrease in CI from May to June. Although it appears that both farms saw two spawning events, clams at the North Farm had a significantly lower CI compared with the South Farm clams for the duration of the summer following the energy expenditure in May. The CI for the North Farm rose above than that of the South Farm in October. The CI data indicate differences in spawning regimes displayed by clams at the two sites.

Individual Growth Experiment

The individual growth experiment showed significantly different growth rates between the sites (Fig. 6), but the difference was less pronounced than in the farmed clams. At the North Farm, the clams grew an average of 10 mm, which was more than the growth measured in the farmed clams (5 mm) over the same time frame. At the South Farm, the clams grew an average of 14 mm over the season, similar to the observed growth of farmed clams there. Although both sites had faster growth during March–July than July–December, the South Farm site had significantly faster growth in each time period (*t*-test: $P = 0.00001$ for March–July, $P = 0.0095$ for July–December).

Age and Growth Analysis

Age and growth were measured on over 300 clam shells (Table 1). When the two faces of the cut valves were compared, they did not reveal the same growth (*t*-test: $P = 0.007$), and therefore these faces were not intermixed in later analyses.

Distance to the third annulus in the hinge for the North Farm samples from 2022 averaged 4.54 mm (±0.13 mm, 95% CI) for April–October. For the South Farm, the distance to the second annulus in April 2023 averaged 4.54 mm (±0.30 mm, 95% confidence interval).

Comparisons between sample sets revealed that clams at the South Farm reached larger sizes in their first 2 y than either clams at the North Farm or wild clams from near both farms

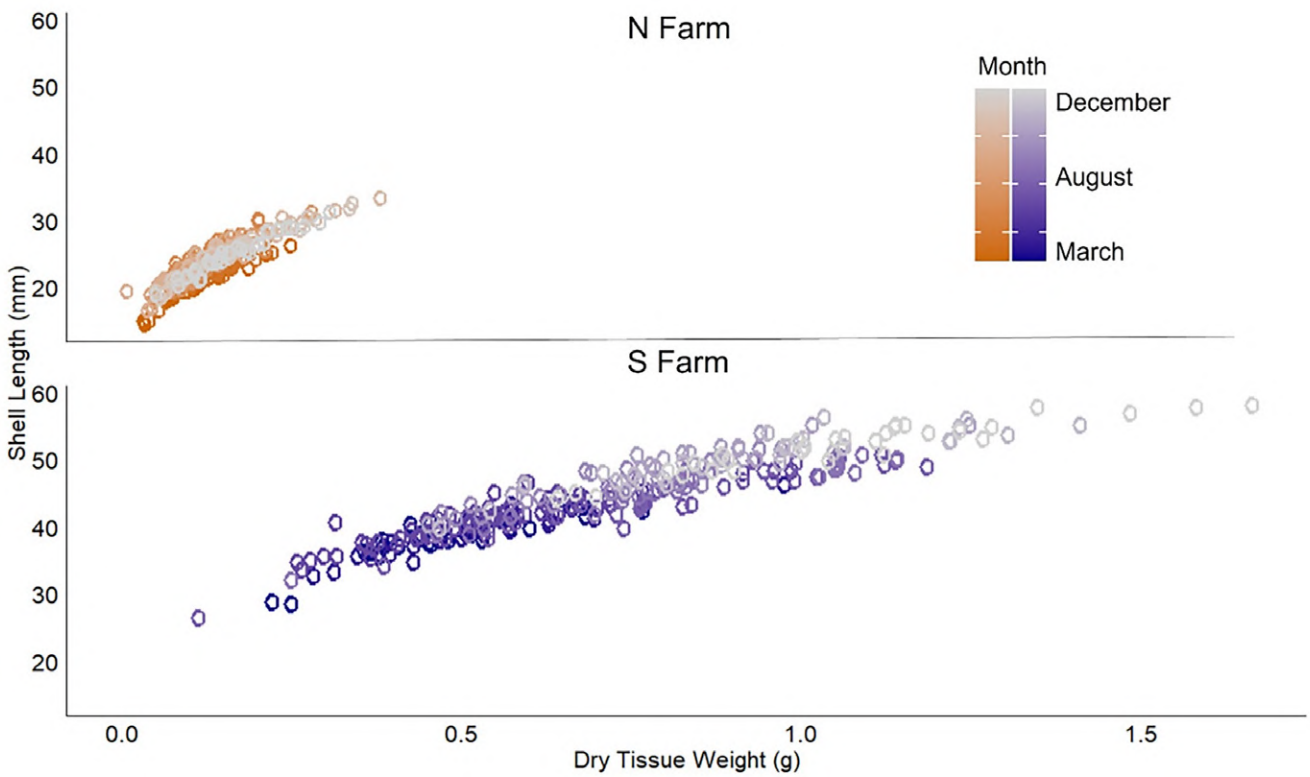

Figure 4. Shell length (mm) versus dry tissue weight (g) from all hard clams measured at each site.

(*t*-test: $P < 0.0001$, Fig. 7). Furthermore, the 2-y-old clams at the South Farm were similar in size to 3-y-old clams at the North Farm (Figs. 7 and 8). The clams at the North Farm grew less in their first 3 y than large clam samples collected there in 2022 (*t*-test: $P = 0.033$, Fig. 8), but they did not differ from large clam samples collected in 2023 (*t*-test: $P = 0.08$).

Environmental Variables

The temperatures at the North Farm were between 5°C and 27°C, whereas the temperatures at the South Farm were between 5°C and 28°C (Fig. 9). The largest difference in temperature between sites was during the spring months, when the temperatures at the South Farm were approximately 2°C warmer than at the North Farm. From mid-June until the end of the study period, the temperatures remained similar between the two farms. According to Ansell (1968), the optimal temperature for

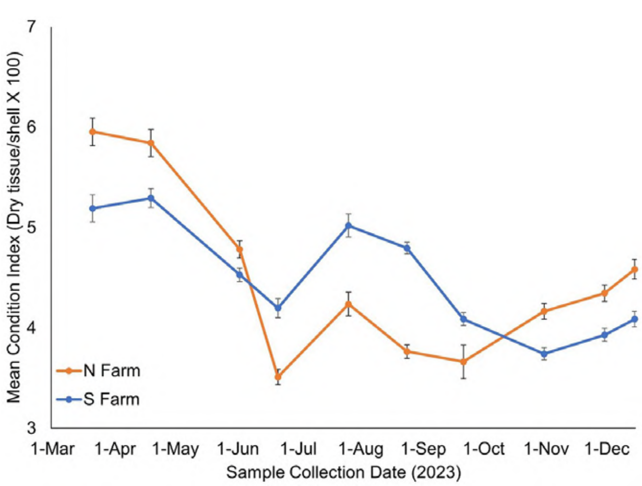

Figure 5. Condition index comparison at both farms throughout the year. Error bars are SE based on 24–30 samples per month from each farm.

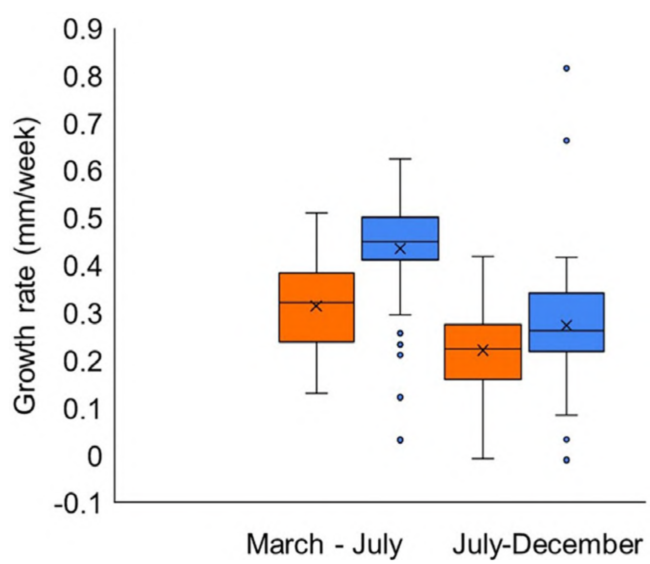

Figure 6. Growth rate comparison between farm sites. North Farm is shown in orange, and South Farm is shown in blue. The "×" represents the mean of the data and the horizontal line is the 50% (median) value. In both seasons, there was a significant difference between farms (March–July: $P = 0.0001$; July–December: $P = 0.0095$).

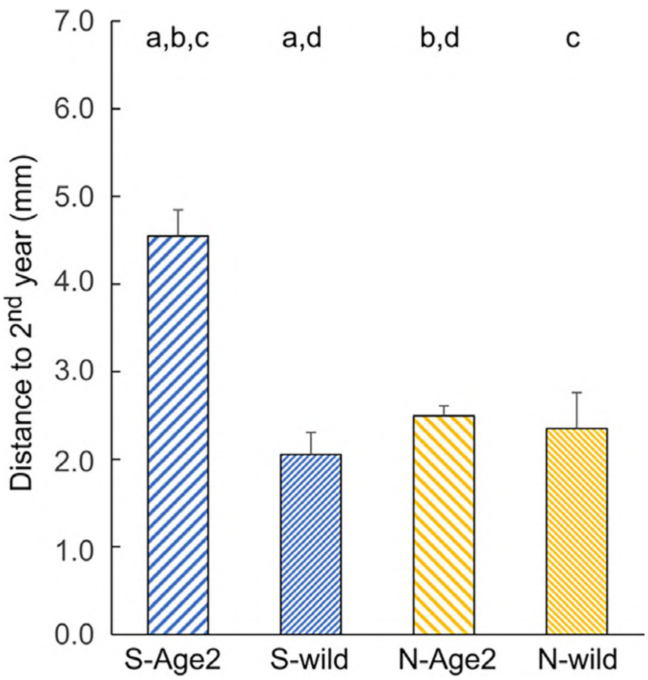

Figure 7. Mean growth to the second year for measured clams. Error bars show a 95% confidence interval. Letters indicate significant differences between groups (a, b, c: $P < 0.0001$, d: $P = 0.004$).

hard clam growth is 20°C–24°C. Clams at both farms spent a similarly small amount of time in this range (Fig. 9).

Current speed (Fig. 10) at the North Farm averaged less than 30 cm s^{-1} for the majority of the season (March–November) and increased gradually in the winter. Only once, during a late summer storm, was a current speed of 100 cm s^{-1} recorded. Average current at the South Farm was similar, at 30 cm s^{-1} during March–October, but had much larger increases during fall and winter, increasing to above 100 cm s^{-1} regularly in late November and December.

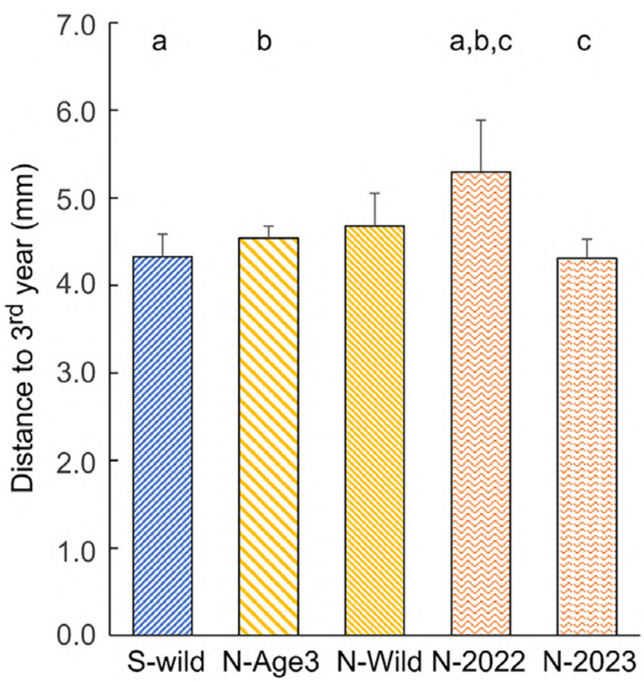

Figure 8. Mean growth to the third year for measured clams. Error bars show a 95% confidence interval. Letters indicate significant differences between groups (a: $P = 0.011$, b: $P = 0.033$, c: $P = 0.009$).

DISCUSSION

This study showed that growth was significantly different between the two aquaculture farms, both in terms of individual growth over the growing season and annual growth across multiple years. Growth at the South Farm was significantly faster in both analyses, on a scale such that clams grown at the South Farm were able to reach market size on average a year earlier than clams at the North Farm.

Although the farmers at the North Farm have reported a reduction in growth in the past few years, the analysis of yearly rings did not consistently show any long-term change in growth. This may be because each of the large clam collections came from a range of spawning years. The experience of farmers who have been working in the area for decades cannot be discounted, despite the lack of clear evidence for a change in growth in this study. Other evidence reflects a decrease in the number of wild clams in Little Egg Harbor over similar time scales (Bricelj et al. 2017).

It is important to note that measuring parameters related to food, including Chl-*a* concentration and phytoplankton community makeup, were outside the scope of this research. Although food availability is one of the most important requirements for successful hard clam growth, there are a few reasons why measuring food was not feasible or necessary for this study, as stated in the Introduction. Without frequent collection of a broad variety of measurements, it is difficult to understand the quantity and quality of food available to support hard clam growth.

In this study, the individual growth experiment which controlled for stocking density was used as a proxy of food availability. The clams stocked at lower densities (versus the stocking density for farmed clams) in the individual growth experiment at the South Farm grew at the same rate as the farmed clams, showing that environmental parameters including food are not limiting for those clams. The North Farm results showed that clams stocked at lower densities grew faster (more like the South Farm) than the farmed clams at the same site. This provides evidence that food or some other environmental parameter is limiting the growth. The lack of differences in current and temperature at each site ruled out these environmental parameters as a cause of the disparity in growth. Also, the individual growth experiment did not explain the full difference in growth rate. This points to the possibility that carrying capacity in the estuary has been reached.

Although food availability was not directly measured in this study, there were signs that it is likely to be a factor in causing the reduced growth. In other bivalve species, it has been shown that animals spend energy on spawning in food-limited conditions and spend more energy on shell and tissue growth when food is in excess (Utting & Millican 1997). The CI results (Fig. 5) showed a steep decline in condition after the spawning season and a slower recovery during the prime growing season at the North Farm. This indicated that the clams were using most of their energy toward spawning rather than shell

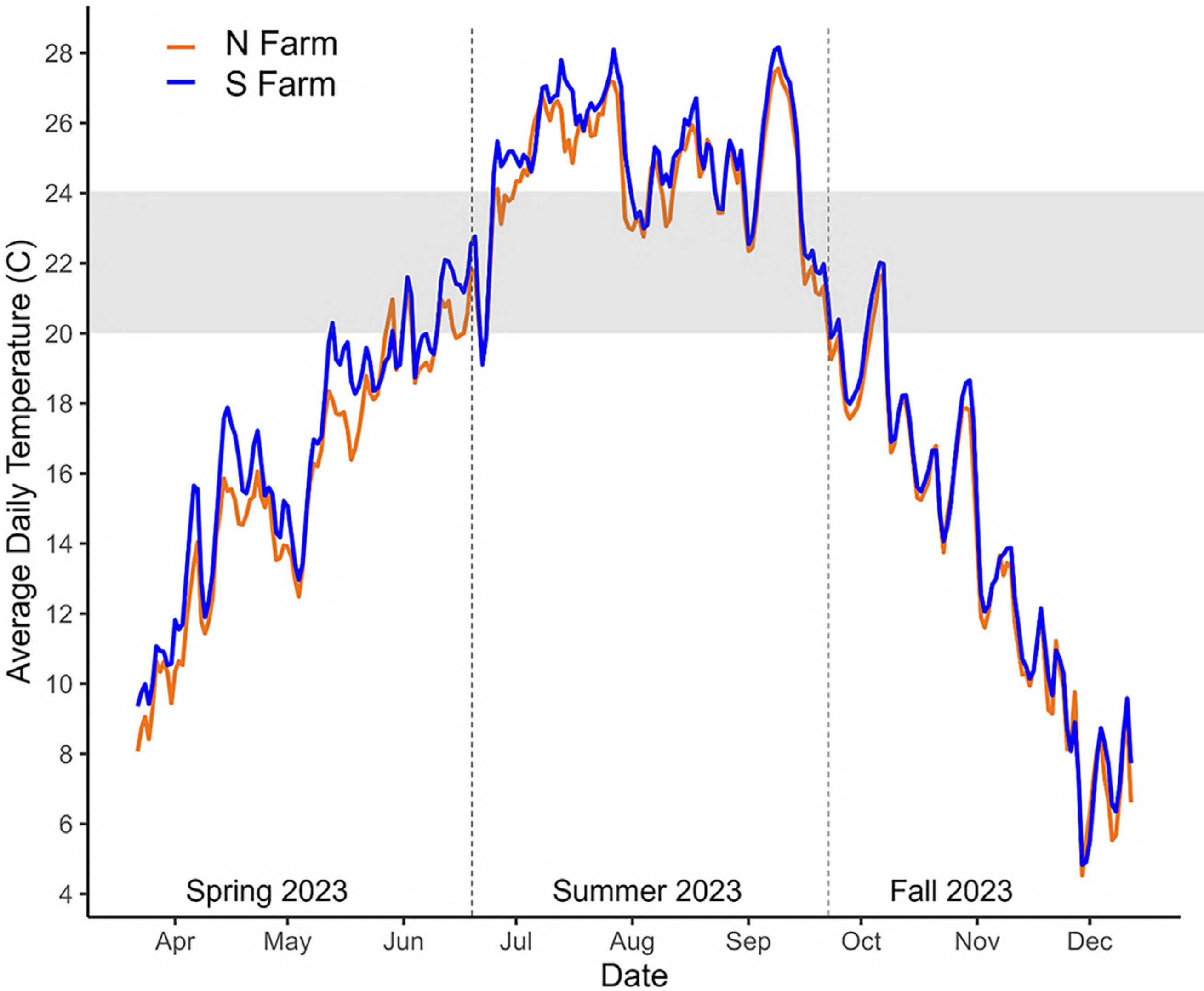

Figure 9. Temperature at each site. Gray box shows the optimal temperature for maximal hard clam growth (Ansell 1968).

and tissue growth, which may explain the large differences in somatic growth over the season (5 mm at the North Farm versus 15 mm at the South Farm).

Lower food availability may be attributed, at least in part, to the lower magnitude of flushing in Little Egg Harbor, as seen in the observed current speeds. Higher current speeds can bring new phytoplankton to the clam location. Increased scouring of the substrate can also resuspend macrobenthos and seston into the water column.

It is possible that the estuary-wide carrying capacity in Little Egg Harbor may be lower than in Great Sound, or that the capacity has been reduced relative to historical levels. When stocking density was controlled in the individual growth experiment, clam growth from the two sites was more similar (10 mm at the North Farm versus 14 mm at the South Farm), but it still differed significantly. Although stocking density may explain some of the differences in growth, it is not the only contributing factor.

Modeling of carrying capacity for shellfish has been done in other estuary systems (Byron et al. 2011, Kuschner 2015). On aquaculture farms on the eastern shore of Virginia, Kuschner (2015) confirmed that carrying capacity limitation was a major contributor to the slow growth of hard clams witnessed there. The results for Little Egg Harbor, NJ show a potentially similar pattern.

Understanding the changes in growth and production efficiency in Little Egg Harbor and other affected areas is vitally important to the hard clam industry in New Jersey and the northeast region of the United States. Hard clam populations in other areas of the northeastern United States have also changed dramatically (Connecticut Department of Agriculture 2024, Soloman et al. 2024), and there have been efforts in Rhode Island, New York, and Connecticut to investigate declines in both farmed and wild-harvested clams (Soloman et al. 2024, Gobler et al. 2022, T. Getchis 2025 personal communication, CT Sea Grant). Greater knowledge of the underlying causes of poor growth in hard clams will aid farmers across the northeast in counteracting the problem.

Results from this study have implications for the efficiency and economics of farming hard clams. The hope is that this information can help farmers make informed choices about their production plans, at the North Farm and on similarly

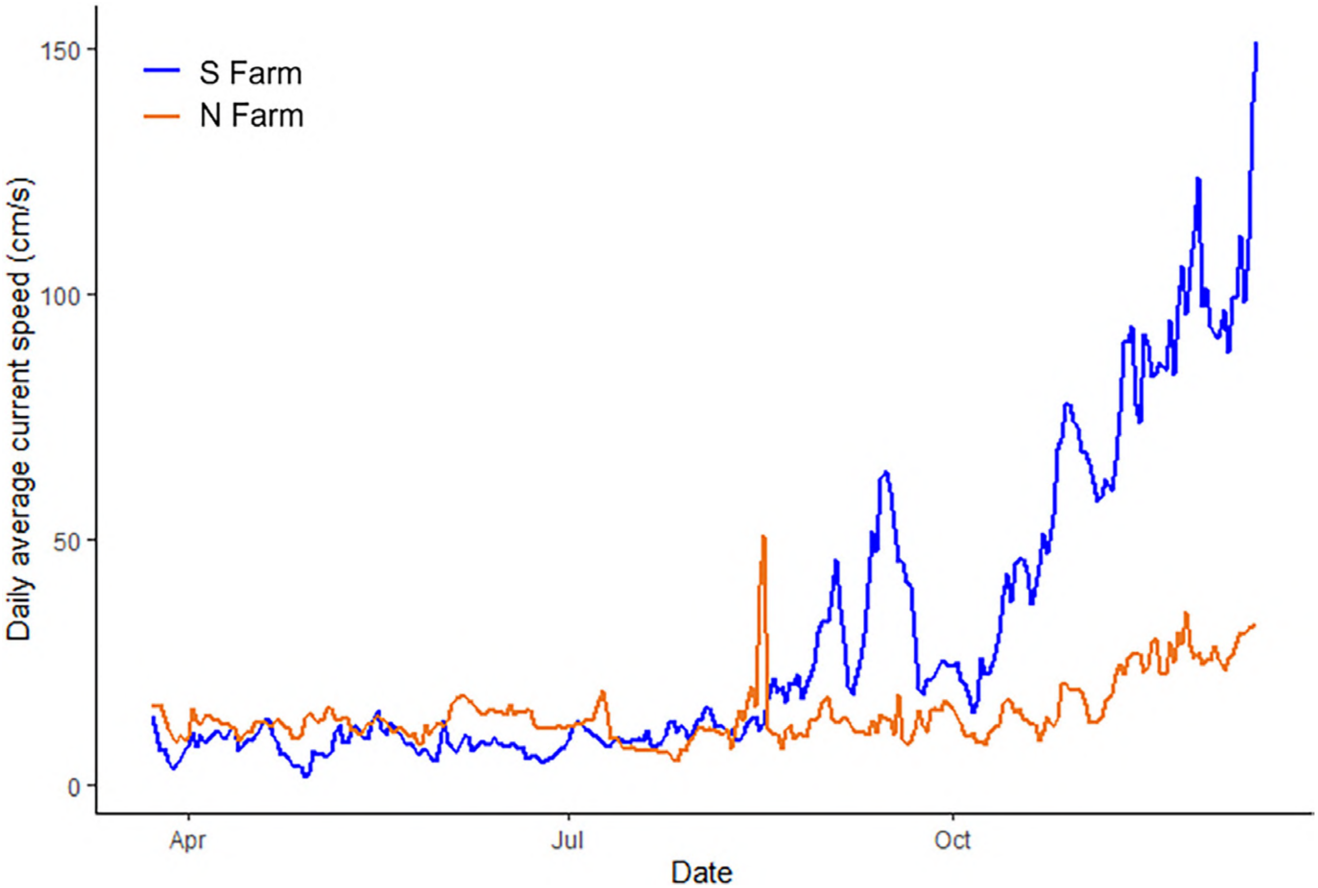

Figure 10. Daily average current speeds (cm s^{-1}) at each site throughout the sampling season.

affected farms. Although the North Farm had a larger quantity of clams than the South Farm, the extra year of growth needed to bring these clams to market size adds significantly to their cost of production. Labor is usually the largest cost on shellfish farms (Engle et al. 2023, Chen et al. 2017), and an extra year worth of labor can significantly reduce farm profitability.

Further Work

Further efforts should aim to investigate environmental variables more deeply, including studies of the seston quality, concentrations, and current speeds throughout the entire area of both farms. These data would allow modeling of the seston flux (per Grizzle and Lutz 1989) for each estuary and to investigate the interplay between food availability and current speed. Additional studies investigating estuary carrying capacity, effects of husbandry practices (stocking density, net size, and cleaning frequency), and growth over a longer time scale would provide essential data for the farmers in the area to make knowledgeable decisions on farming practices in the future.

CONCLUSIONS

A combination of CI measurements, a growth study, analysis of annual marks, and environmental measurements were used to understand the production dynamics of two nearby hard clam farms in New Jersey.

Hard clam growth differed significantly between the estuaries, as evidenced by both monthly measurements and analysis of annual marks. Clams at the South Farm grew faster, reaching market size a year before clams at the North Farm, as well as reaching larger sizes in the first 2 y than wild clams at both sites. Based upon the results of the individual growth study and measures of condition, stocking density can explain some of the difference. Additionally, specific factors contributing to growth differences remain unknown, as there were no significant temperature differences, and the current speeds differed only in winter. Although the cause of reduced growth at the North Farm remains unclear, the study uncovered several potential reasons for it. Most evident are husbandry practice differences (overstocking) and the North Farm estuary potentially exceeding carrying capacity. Further studies on seston concentration and carrying capacity modeling could provide more specific conclusions. Hopefully, the lessons learned from this project can be applied to studying hard clam aquaculture throughout the northeast.

ACKNOWLEDGMENTS

We would like to thank the USDA SARE Partnership Grant Program for funding the work conducted for this research study via Project #ONE22-415. We thank Gary Wikfors for his support and expertise throughout the project, introducing project partners, and editing the manuscript. We thank Meghana Parikh, Bella Wasserman–Shultz, Indya Lumpkin, Molly Roberts, and others who have assisted in some portion of the field work, planning, or laboratory work for the project. We also thank our farm partners for allowing us to work on the farms and sending clam samples regularly to the laboratory and the New Jersey Department of Environmental Protection for their assistance in collecting wild clams from each site.

LITERATURE CITED

Ansell, A. D. 1968. The rate of growth of the hard clam (*Mercenaria mercenaria* L) throughout the geographical range. *ICES J. Mar. Sci.* 31:364–409.

Bricelj, V. M. 2009. The Hard Clam Research Initiative: factors controlling *Mercenaria mercenaria* populations in south shore bays of Long Island, NY. Stony Brook, NY: New York Sea Grant. pp. 1–43.

Bricelj, V. M., J. N. Kraeuter & G. Flimlin. 2017. Status and trends of hard clam, *Mercenaria mercenaria*, populations in a coastal lagoon ecosystem, Barnegat Bay–Little Egg Harbor, New Jersey. *J. Coast. Res.* 78:205–253.

Byron, C., D. Bengtson, B. Costa–Pierce & J. Calanni. 2011. Integrating science into management: ecological carrying capacity of bivalve shellfish aquaculture. *Mar. Policy* 35:363–370.

Calvo, L. M. 2017. New Jersey shellfish aquaculture situation and outlook report 2015 production year. New Jersey Agricultural Experiment Station.

Chen, J. Q., M. C. Haws, Q. S. W. Fong & P. Leung. 2017. Economic feasibility of producing oysters using a small-scale Hawaiian fishpond model. *Aquac. Rep.* 5:41–51.

Connecticut Department of Agriculture. 2024. Shellfish industry profile and economic impact. Available at: https://portal.ct.gov/doag/aquaculture1/aquaculture/shellfish-industry-profile.

Engle, C. R., J. Van Senten, M. H. Schwarz, C. Brayden & S. Belle. 2023. Developing production and financial benchmarks for marine aquaculture from farm data. *Aquac. Econ. Manag.* 27:352–381.

Galimany, E., J. Lunt, C. J. Freeman, S. Reed, I. Segura–García & V. J. Paul. 2017. Feeding behavior of eastern oysters *Crassostrea virginica* and hard clams *Mercenaria mercenaria* in shallow estuaries. *Mar. Ecol. Prog. Ser.* 567:125–137.

Gobler, C. J., M. H. Doall, B. J. Peterson, C. S. Young, F. DeLaney, R. B. Wallace, S. J. Tomasetti, T. P. Curtin, B. K. Morrell, E. M. Lamoureux, B. Ueoka, A. W. Griffith, J. M. Carroll, D. Nanjappa, J. G. Jankowiak, J. A. Goleski, A. M. E. Famularo, Y. Kang, E. K. Pikitch, C. Santora, S. M. Heck, D. M. Cottrell, D. W. Chin & R. E. Kulp. 2022. Rebuilding a collapsed bivalve population, restoring seagrass meadows, and eradicating harmful algal blooms in a temperate lagoon using spawner sanctuaries. *Front. Mar. Sci.* 9:1–22.

Grizzle, R. E. & R. A. Lutz. 1989. A statistical model relating horizontal seston fluxes and bottom sediment characteristics to growth of *Mercenaria mercenaria*. *Mar. Biol.* 102:95–105.

Grizzle, R. E., V. M. Bricelj & S. E. Shumway. 2001. Chapter 8 Physiological ecology of *Mercenaria mercenaria*. *Dev. Aquac. Fish. Sci.* 31:305–382.

Jones, D. S., I. R. Quitmyer, W. S. Arnold & D. C. Marelli. 1990. Annual shell banding, age, and growth rate of hard clams (*Mercenaria* Spp.) from Florida. *J. Shellfish Res.* 9:215–225.

Kuschner, M. A. 2015. A model of carrying capacity and ecosystem impacts in a large-scale, bivalve-dominated agro-ecosystem: hard clam aquaculture in Cherrystone Inlet, VA. MS thesis, William & Mary. 85 pp.

Lucas, A. & P. G. Beninger. 1985. The use of physiological condition indices in marine bivalve aquaculture. *Aquaculture* 44:187–200.

Peterson, C. H., P. B. Duncan, H. C. Summerson & A. W. Safrit. 1983. A mark-recapture test of annual periodicity of internal growth band deposition in shells of hard clams, *Mercenaria mercenaria*, from a population along the southeastern United States. *Fish. Bull.* 81:765–799.

Peterson, C. H., P. B. Duncan, H. C. Summerson & B. F. Beal. 1985. Annual band deposition within shells of the hard clam, *Mercenaria mercenaria:* consistency across habitat near Cape Lookout, North Carolina. *Fish. Bull.* 83:671–677.

Ridgway, I. D., C. A. Richardson, E. Enos, Z. Ungvari, S. N. Austad, E. E. R. Philipp & A. Csiszar. 2011. New species longevity record for the northern quahog (=hard clam), *Mercenaria mercenaria*. *J. Shellfish Res.* 30:35–38.

Schneider, C. A., W. S. Rasband & K. W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* 9:671–675.

Soloman, J. J., A. M. DiMario, D. A. Bennett, D. Borkman, J. Willis, M. Gomez–Chiarri, H. Abdelrahman, W. Palm, M. Jarbeau, J. King, M. McGiveney, J. Boyd & M. Johnson. 2024. Special Legislative Commission to study and provide recommendations on the issues relating to the reduced catch of quahogs in Narragansett Bay: final report. Report. Rhode Island House of Representatives and Rhode Island Senate.

Utting, S. D. & P. F. Millican. 1997. Techniques for the hatchery conditioning of bivalve broodstocks and the subsequent effect on egg quality and larval viability. *Aquaculture* 155:45–54.

Yang, H., L. N. Sturmer & S. Baker. 2016. Molluscan shellfish aquaculture and production. Program in Fisheries and Aquatic Sciences of the School of Forest Resources and Conservations, UF/IFAs. FA191:1–8.

Zeng, Y. & H. Yang. 2020. Review of molluscan bivalve condition index calculations and application in northern quahogs *Mercenaria mercenaria*. *Aquac. Res.* 52:23–36.