

The effects of ocean warming and acidification on the growth of commercially important shellfish species

Olivia Boyan

Introduction

Shellfish, or bivalves, are important species ecologically and commercially. Shellfish are filter feeders which means they obtain food by filtering particles and plankton from the water column (Vaughn and Hoellein 2018). This action of filtering removes particles from the water column which cleans the water providing an ecosystem service by improving water quality (Coen et al. 2007; Vaughn and Hoellein 2018). Filtration from shellfish also provide nutrient remediation services by removing nitrogen and phosphorus from the water which can provide other marine organisms that use shellfish reefs as habitat with benefits (Schatte Olivier et al. 2020). Shellfish are also economically important as they are a popular food source. In 2022, 13,943,751 pounds of shellfish were grown in aquaculture in the Northeastern United States with a value of \$133,100,988 (Fisheries 2025).

As filter feeders, shellfish can consume unfavorable prey items including toxin-producing algae (Rourke et al. 2022). The consumption of such algae can result in the accumulation of phycotoxins in shellfish tissue (Rourke et al. 2022). Toxins produced by these algae such as paralytic shellfish poisons (PSP) and domoic acid (DA) can be harmful to human health if consumed (Shumway 1990; Grattan, Holobaugh, and Morris 2016; Rourke et al. 2022). Shellfish are generally classified as filter feeders, however, there have been observed differences in phycotoxin accumulation between species as a result of species-species differences in clearance rates and particle selectivity (Mafra, Bricelj, and Fennel 2010). An example of this includes oysters which have been found to have higher particle selectivity and lower clearance rates compared to other bivalves which means they are able to select particles of a desired size and type as well as ingest fewer particles from the water column (Mafra, Bricelj, and Fennel 2010). Other bivalves, including mussels and scallops, have been found to be less selective in what they consume (Sauvey et al., n.d.; Rourke et al. 2022; Mafra, Bricelj, and Fennel 2010; Hégaret et al. 2008). Understanding the relationship between species-species feeding behaviors and toxin

accumulation is important for managing risks associated with human health and improving the sustainability of the shellfish industry.

Understanding these differences is important as harmful algal blooms (HABs) increase in duration and intensity along with the elevated effects of ocean warming and acidification, particularly in the Gulf of Maine (GoME) which is changing faster than other bodies of water (Anderson et al. 2014; Gobler et al. 2017; Seto, Karp-Boss, and Wells 2019; Brickman et al. 2021; Pershing et al. 2015; Siedlecki et al. 2021). HABs involve an abundance of multiple species of algae that produce toxins or bioactive compounds which often cause the closures of shellfish harvesting to manage the risk of toxin consumption from humans (Anderson et al. 2014; Anderson et al. 2021; Fernandes-salvador et al. 2021; Davidson et al. 2016; Grizzle and Ward 2016). Toxin level monitoring is often based on mussels as the ideal species since they accumulate toxins quickly, providing early detection of HABs (Rourke et al. 2022; Bricelj and Shumway 1998). While mussels are a good indicator of toxin levels, they may not be appropriate to assume the toxin levels found in other bivalve species as toxin accumulation can vary between species under current environmental conditions by up to 100-fold (Mafra, Bricelj, and Fennel 2010; Rourke et al. 2022; Sauvey et al., n.d.). Understanding these species-species differences in toxin accumulation can provide information on how to monitor the locations from which each shellfish species is harvested from rather than applying toxin monitoring from mussels to all shellfish species.

In addition to HABs, the metabolic rates of shellfish can also be affected by ocean warming and acidification (Crain, Kroeker, and Halpern 2008; Kordas, Harley, and O'Connor 2011; Kroeker et al. 2013; Lefevre 2016; Braga et al. 2018). Increased temperatures from ocean warming can cause these shellfish to have a higher metabolic demand leading to changes in clearance rates, particle selectivity, growth rate, and detoxification processes (Anestis et al. 2007; O'Connor 2009; Todgham and Stillman 2013; Gunderson, Armstrong, and Stillman 2016; Lowe et al. 2017). Coastal acidification can also affect the metabolic rates of shellfish by altering acid base physiology and energy demands (Portner, Langenbuch, and Reipschlager 2004; Widdicombe and Spicer 2008; Salisbury et al. 2011). Based on this information, predicted future water conditions are likely to cause significant impacts on feeding selectivity and toxin uptake of commercially important shellfish species (Braga et al. 2018).

To understand and predict the impact of these future water conditions on the shellfish industry in New Hampshire, it is necessary to research the effects of coastal stressors on the feeding behavior, food selectivity, and phycotoxin accumulation processes in commercially important bivalve species. This research was conducted to recognize how species are impacted by predicted changes in water conditions as well as to support the mitigation of negative impacts from HABs on the shellfish industry through the development of management strategies.

This paper looks at how predicted water temperatures and acidification levels affect metabolic rates, specifically growth, in commercially important shellfish species as part of the overall goal of this research. It is hypothesized that shellfish subjected to either increased temperatures, ocean acidification conditions, or a combination of both, will show less growth than individuals

subjected to current summer ambient conditions in New Hampshire. It is also hypothesized that shellfish growth will differ between species.

Methods

Experimental Design

This experiment was conducted at the University of New Hampshire's Coastal Marine Lab which has a system of aquaria that allows for precise control over partial pressure carbon dioxide (pCO_2) and temperature. This system consists of 20 tanks that can be controlled individually to replicate experimental water conditions. For this experiment, four water condition treatments were randomly selected for each tank so that there were five tanks of each treatment in the system Figure 1. These treatments included ambient which was set to the ambient summer conditions of the area (17 degrees C, pH 8.0), ocean warming which was set to four degrees above ambient and pH 8.0 (21 degrees C, pH 8.0), ocean acidification which was set to ambient temperatures and pH 7.5 (17 degrees C, pH 7.5), and multi-stressor which was set to ocean warming temperatures and ocean acidification pH (21 degrees C, pH 7.5). Each tank was split into nine boxes and each box could hold four individuals from the same species. Each column of boxes was randomly designated a species Figure 2. These species included Eastern oysters (*Crassostrea virginica*), Blue mussels (*Mytilus edulis*), and Atlantic sea scallops (*Placopecten magellanicus*).

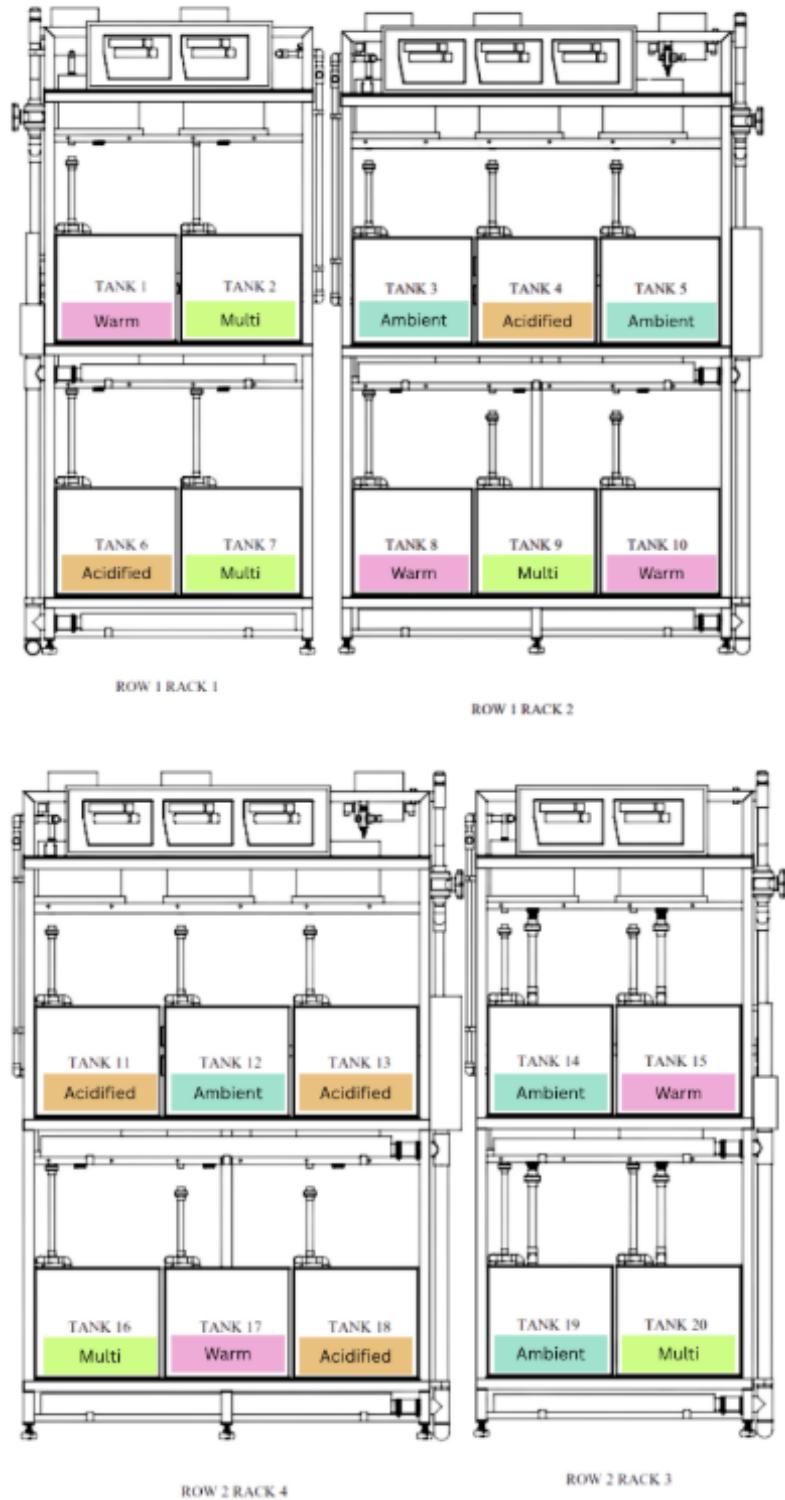


Figure 1: Assignment of treatment conditions (Ambient, Warm, Acidification, Multi) for each of the 20 tanks in the system. (Photo: Hannah Gossner)

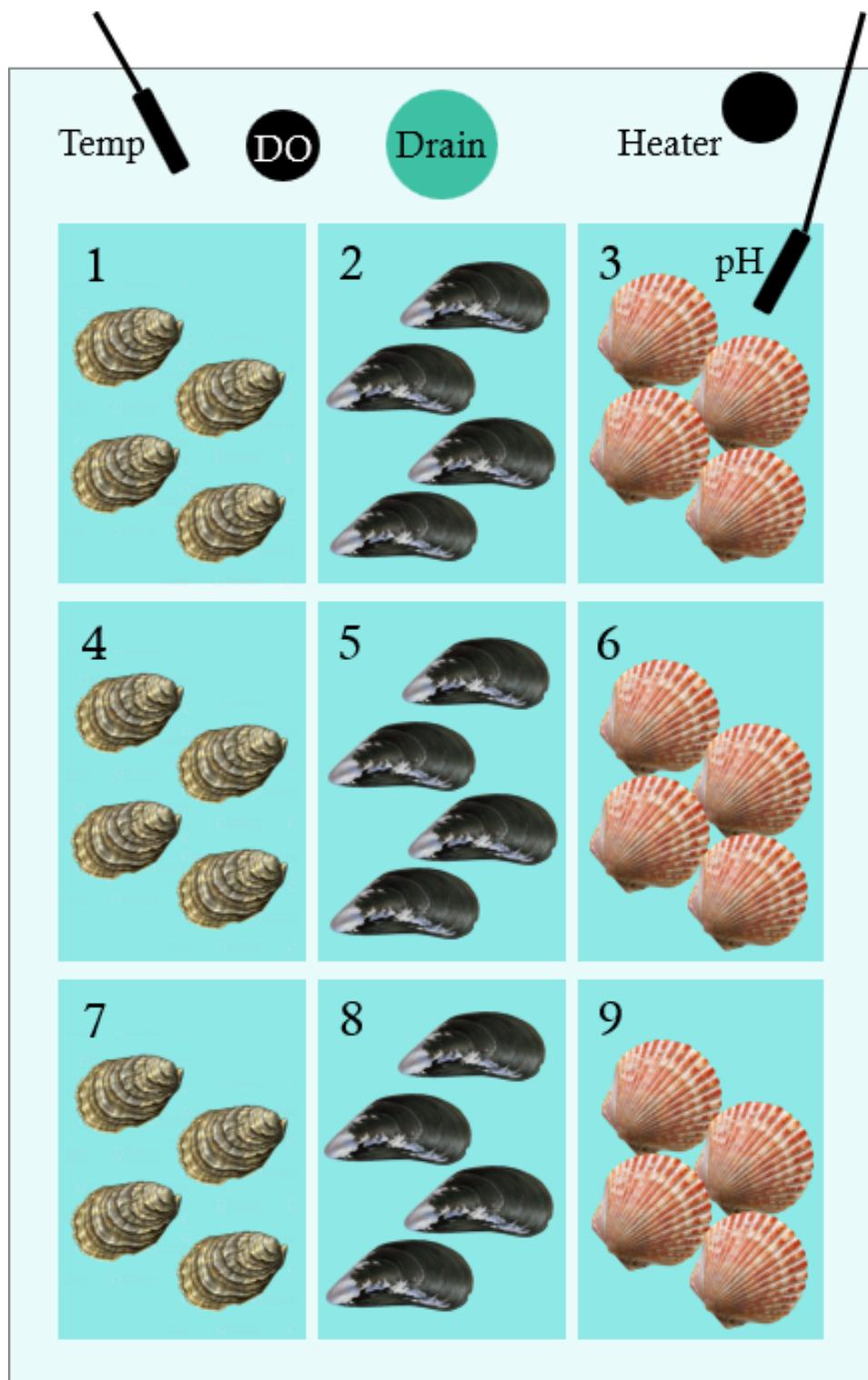


Figure 2: Layout of each tank with the nine boxes. Each box was able to hold four individuals. Each column, designated from where the drain is, was randomized for which species they would hold.

Shellfish were collected from local farms to have 240 individuals of each species. These individuals were measured for length (mm), width (mm), and depth (mm) and weighed (g) (Gimin et al. 2004). Once measured they were placed in their designated tank spaces. Once all shellfish were in their tank spaces, they were subjected to an acclimation period of two weeks with no experimental conditions to adjust to living in the tanks. After that they were subjected to an environmental acclimation period of 28 days with treatment conditions. The shellfish were then subject to a selective feeding period of 6 days and then a depuration period of 10 days where on days 1, 3, 6 and 10 shellfish were removed from tanks to have their tissues collected. On these days the shellfish were measured and weighed wet before tissue sampling. All shellfish measurement and weight data was collected onto an Excel csv file.

Data Cleaning and Analysis

The measurement and weight data was cleaned and analyzed using R Studio. The measurement and weight Excel file was loaded into R Studio using the readxl package (Wickham and Bryan 2025). Unnecessary columns and data with “NA”s were removed using the dplyr package (Wickham et al. 2023). Some of the shellfish died which caused there to be missing data for measurements and weight.

The change in length, width, depth and weight was calculated for each shellfish and added as a column using the dplyr package (Wickham et al. 2023). The changes in measurements and weight compared to species and treatments were then graphed as box plots using the ggplot2 package (Wickham 2016).

The difference between species compared to the measurements and weights was analyzed through one-way ANOVAs (2023). A post-hoc tukey test was calculated for ANOVAs with significant results (2023). The difference between treatment compared the measurements and weights was also analyzed through one-way ANOVAs and post-hoc tukey tests (2023).

Results

Change in measurements versus treatment

The change in shellfish weight (g) was found to have a difference between treatments ($F(3, 674) = 2.714, p = 0.044$) Figure 3. This difference in shellfish weight was only apparent between ambient and acidified conditions, where shellfish in ambient conditions had a greater change in weight than shellfish in acidified conditions ($p = 0.0586, 95\% \text{ C.I.} = -0.019, 1.58$) Figure 3. Change in shellfish width (mm) was not different between treatments, indicating that change in shellfish width does not correlate with differences in water conditions ($F(3, 674) = 1.136, p = 0.334$) Figure 4. Change in shellfish length (mm) was also not different between treatments, indicating that change in shellfish length does not correlate with differences in water conditions ($F(3, 674) = 1.687, p = 0.168$) Figure 5. The change in shellfish depth (mm)

was found to have a difference between treatments ($F(3, 674) = 2.714$, $p = 0.044$) Figure 6. This difference in depth was apparent between warm and ambient conditions, where shellfish in ambient conditions had a greater change in depth than shellfish in warm conditions ($p = 0.0385$, 95% C.I. = -1.46, -0.0269), and between warm and multi conditions, where shellfish in multi conditions had a greater change in depth than shellfish in warm conditions ($p = 0.0417$, 95% C.I. = -1.44, -0.0185) Figure 6.

Overall, shellfish weight from ambient conditions changed more than shellfish in acidified conditions while all other treatments showed no variation between each other Figure 3. Shellfish depth from ambient and multi conditions changed more than shellfish in warm conditions while acidified conditions showed no variation between the other treatments Figure 6. Change in shellfish width and length did not vary between treatments Figure 4; Figure 5.

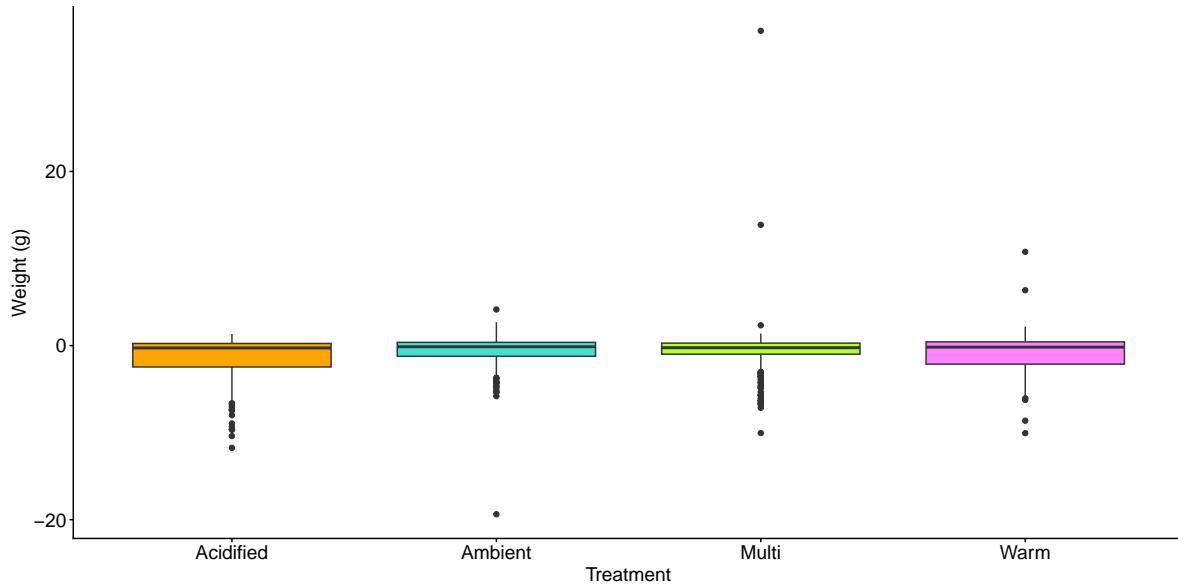


Figure 3: Change in shellfish weight (g) showed a difference between treatments ($F(3, 674) = 2.714$, $p = 0.044$). Change in shellfish weight was only different between ambient and acidified conditions ($p = 0.0586$, 95% C.I. = -0.019, 1.58).

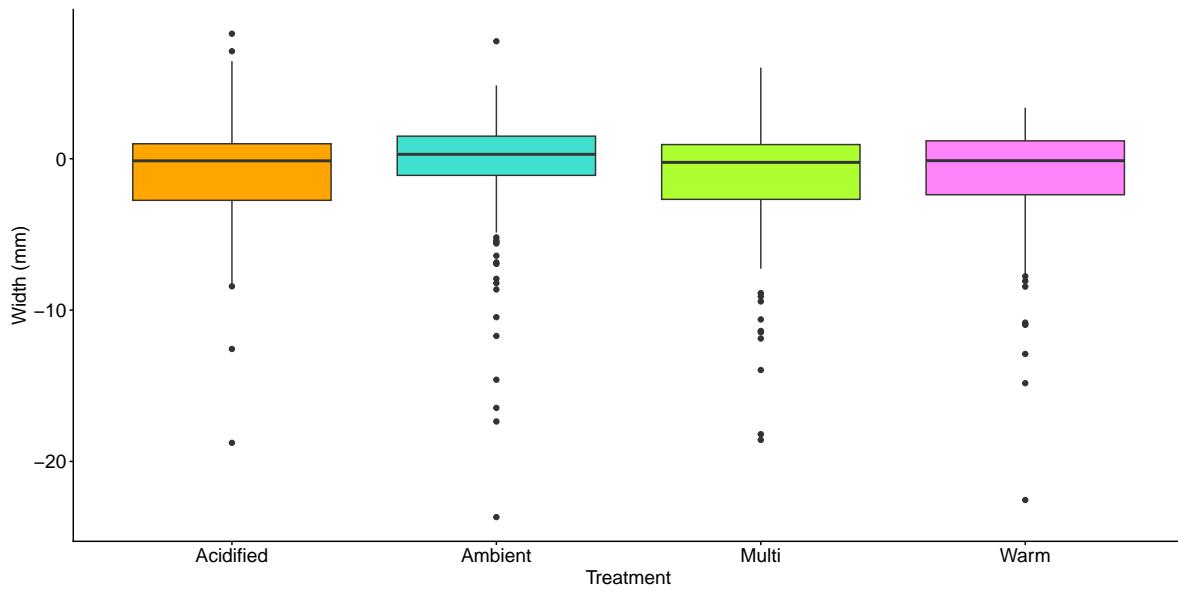


Figure 4: Change in shellfish width (mm) was not different between treatments (Acidified, Ambient, Multi, Warm) ($F(3, 674) = 1.136, p = 0.334$).

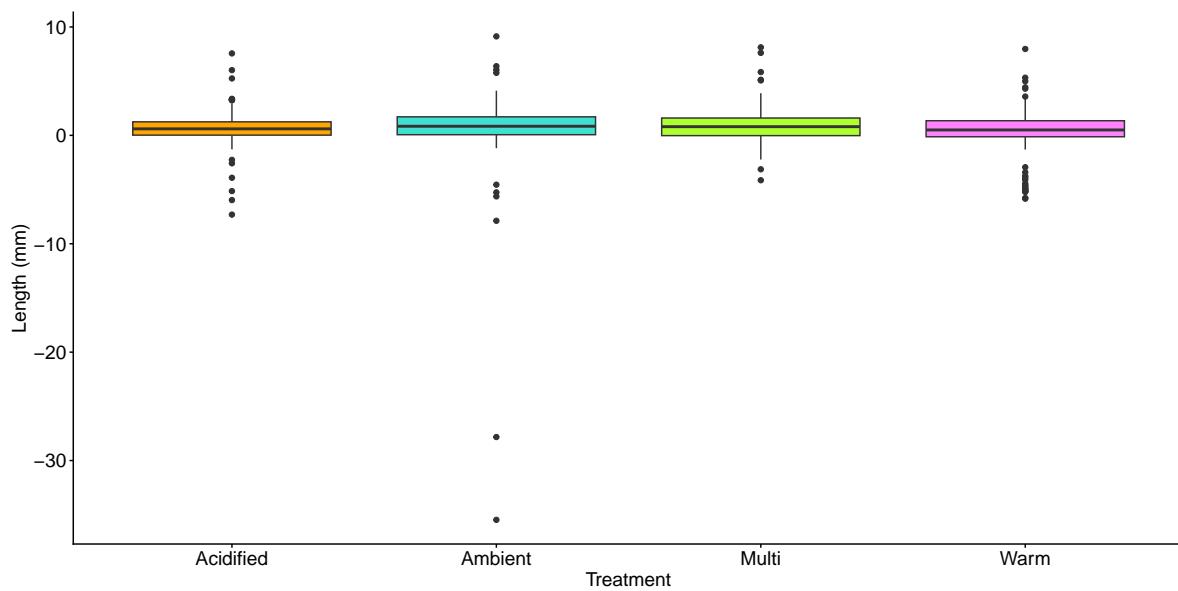


Figure 5: Change in shellfish length (mm) was not different between treatments (Acidified, Ambient, Multi, Warm) ($F(3, 674) = 1.687, p = 0.168$).

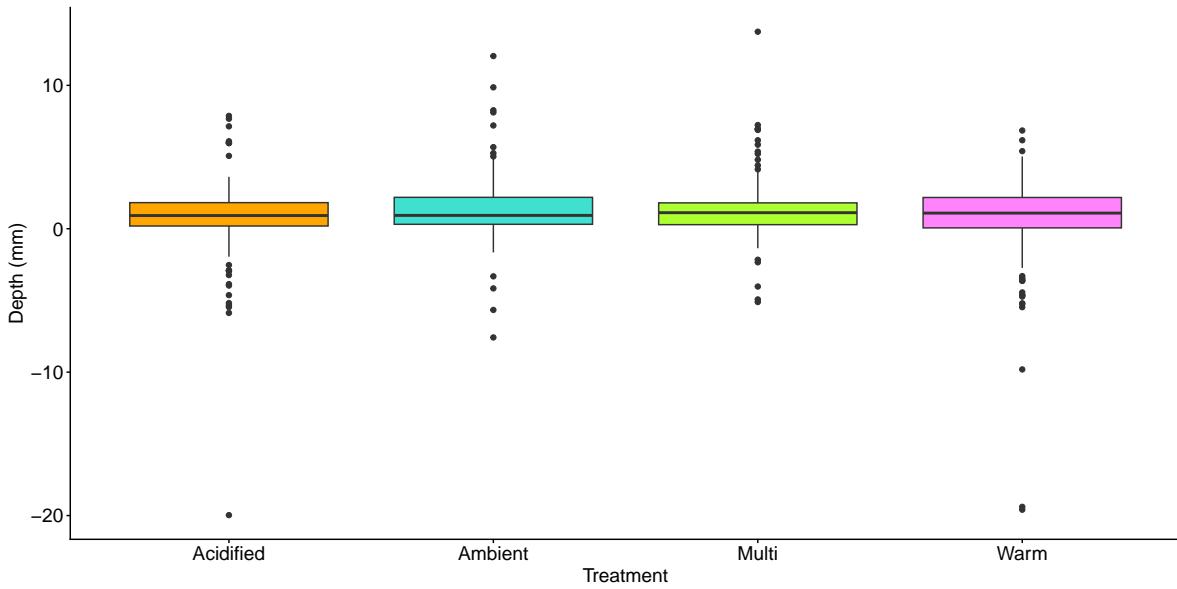


Figure 6: Change in shellfish depth (mm) showed a difference between treatments ($F(3, 674) = 2.714, p = 0.044$). Change in shellfish depth was different between warm and ambient conditions ($p = 0.0385, 95\% \text{ C.I.} = -1.46, -0.0269$) and between warm and multi conditions ($p = 0.0417, 95\% \text{ C.I.} = -1.44, -0.0185$).

Change in measurements versus species

The change in shellfish weight (g) was found to have a difference between species ($F(2, 675) = 186.9, p = <2e-16$) Figure 7. This difference in weight was apparent between oysters and mussels, with mussels having a greater change in weight than oysters ($p = 1.52e-05, 95\% \text{ C.I.} = -1.47, -0.477$), scallops and mussels, with mussels having a greater change in weight than scallops ($p = 0.00e+00, 95\% \text{ C.I.} = -4.56, -3.54$), and scallops and oysters, with oysters having a greater change in weight than scallops ($p = 0.00e+00, 95\% \text{ C.I.} = -3.59, -2.56$) Figure 7. Change in shellfish width (mm) was found to have a difference between species ($F(2, 675) = 78.85, p = <2e-16$) Figure 8. This difference in width was apparent between oysters and mussels, with mussels having a greater change in width than oysters ($p = 5e-07, 95\% \text{ C.I.} = -2.32, -0.897$), scallops and mussels, with scallops having a greater change in width than mussels ($p = 0.00e+00, 95\% \text{ C.I.} = 1.56, 3.02$), and scallops and oysters, with scallops having a greater change in width than oysters ($p = 0.00e+00, 95\% \text{ C.I.} = 3.17, 4.64$) Figure 8. Change in shellfish length (mm) was not different between species, indicating that change in shellfish length does not correlate with species (Mussels, Oysters, Scallops) ($F(2, 675) = 0.627, p = 0.535$) Figure 9. Change in shellfish depth (mm) was found to have a difference between species ($F(2, 675) = 6.182, p = 0.00219$) Figure 10. This difference in depth was apparent between oysters and mussels, with oysters having a greater change in depth than mussels ($p = 0.00827$,

95% C.I. = 0.15, 1.26) and scallops and mussels, with scallops having a greater change in depth than mussels ($p = 0.00609$, 95% C.I. = 0.177, 1.31) Figure 10.

Overall, mussel weight changed the most after treatments while scallops had the least amount of change in weight Figure 7. Scallop width changed the most after treatments while oysters had the least amount of change in width Figure 8. Oyster and scallop depth changed the most after treatments than mussels Figure 10. Change in shellfish length did not vary between species Figure 9.

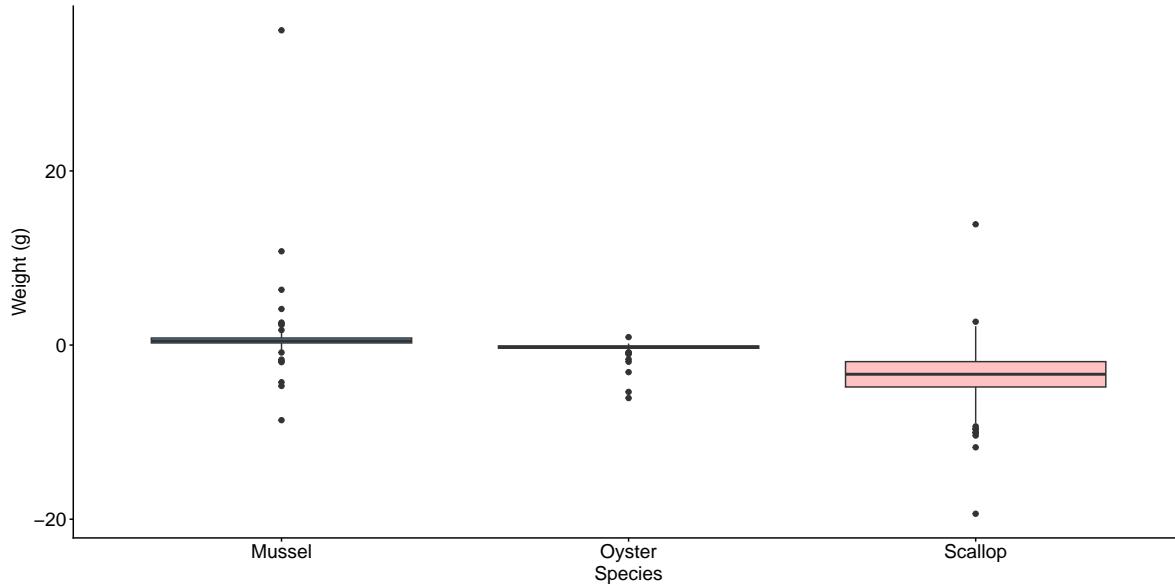


Figure 7: Change in shellfish weight (g) showed a difference between species ($F(2, 675) = 186.9$, $p = <2e-16$). Change in shellfish weight was different between oysters and mussels ($p = 1.52e-05$, 95% C.I. = -1.47, -0.477), scallops and mussels ($p = 0.00e+00$, 95% C.I. = -4.56, -3.54), and scallops and oysters ($p = 0.00e+00$, 95% C.I. = -3.59, -2.56).

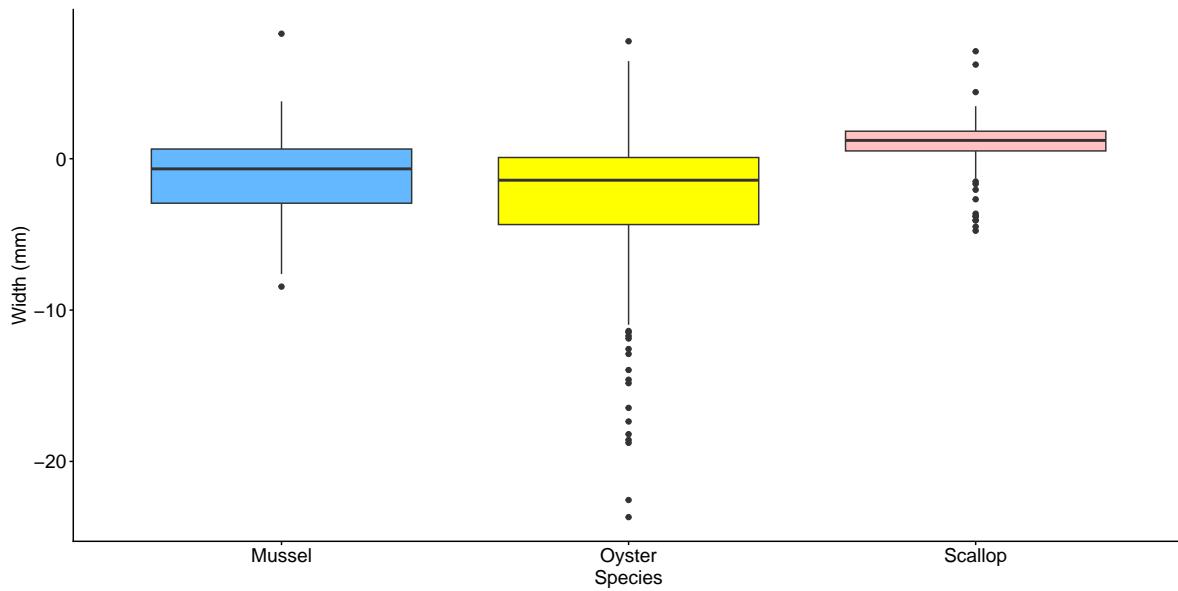


Figure 8: Change in shellfish width (mm) showed a difference between species ($F(2, 675) = 78.85$, $p = <2e-16$). Change in shellfish width was different between oysters and mussels ($p = 5e-07$, 95% C.I. = -2.32, -0.897), scallops and mussels ($p = 0.00e+00$, 95% C.I. = 1.56, 3.02), and scallops and oysters ($p = 0.00e+00$, 95% C.I. = 3.17, 4.64).

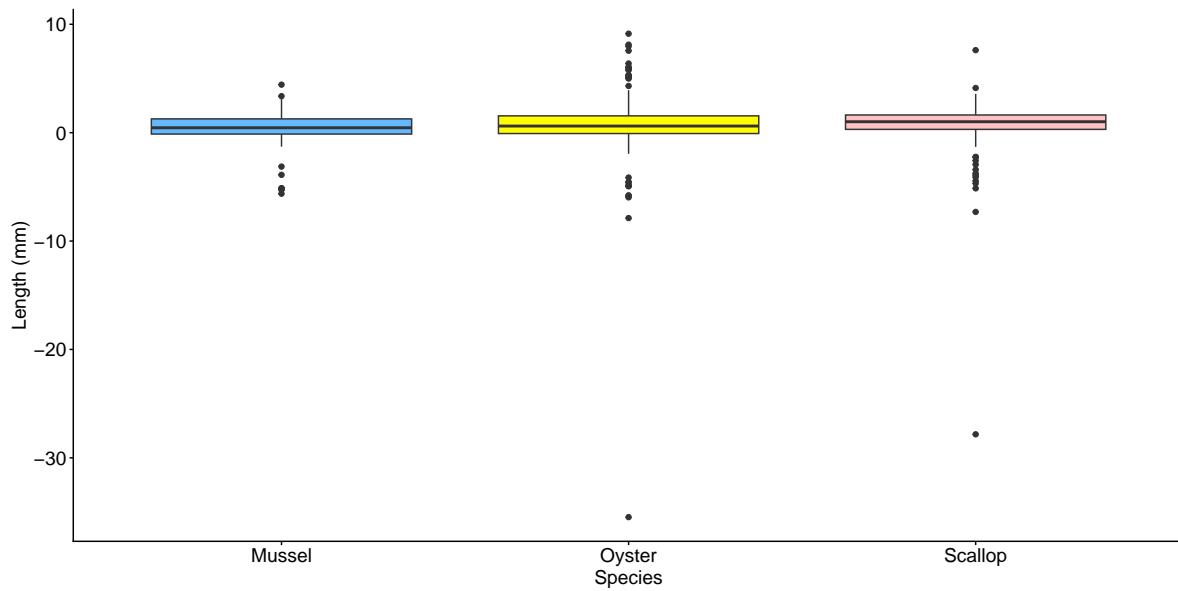


Figure 9: Change in shellfish length (mm) was not different between species (Mussels, Oysters, Scallops) ($F(2, 675) = 0.627$, $p = 0.535$).

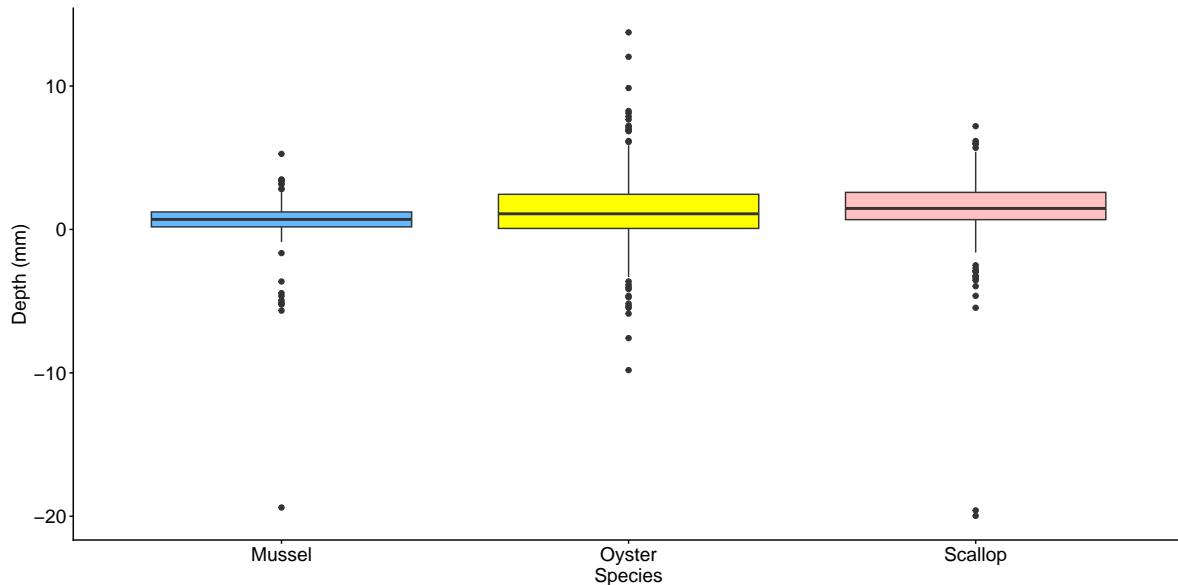


Figure 10: Change in shellfish depth (mm) showed a difference between species ($F(2, 675) = 6.182$, $p = 0.00219$). Change in shellfish depth was different between oysters and mussels ($p = 0.00827$, 95% C.I. = 0.15, 1.26) and scallops and mussels ($p = 0.00609$, 95% C.I. = 0.177, 1.31).

Discussion

This results of this study demonstrate that shellfish growth depends on ocean conditions and differs between species. Shellfish exposed to acidified, warm, and multi-stressor conditions grew less than shellfish exposed to ambient conditions specifically for weight and depth. In addition to this, shellfish growth showed species-species differences in weight, width, and depth. These differences in growth between treatments as well as species-species differences are likely due to tolerances of ocean conditions.

Oysters are highly tolerant to a broad spectrum of temperatures, particularly high water temperatures which can stimulate growth; however, too high of temperatures limits growth (Rybovich et al. 2016; Lowe et al. 2017). There have been limited studies on the growth of oysters in relation to ocean warming and acidification making it difficult to compare results. Despite the lack of research for oysters, previous studies have found changes in the growth of scallops (Lagos et al. 2016). In the study by Lagos et al., scallop weight decreased with high temperature conditions, depth decreased with high temperature, acidified, and multi-stressor conditions, and length decreased with high temperature and acidified conditions (Lagos et al. 2016). Previous studies have also looked at mussel growth but found no significant reduction in growth of individuals subjected to acidified and high temperature conditions; however, they have shown changes in shape, becoming rounder and flatter, as well as changes in shell thickness, becoming thinner (Fitzer et al. 2015). This information appears to be consistent with the results of this study; however, this study found changes in mussel growth unlike Fitzer et al.; however, they used different growth metrics (Fitzer et al. 2015).

Limitations in this study must be considered as they may have affected the results. One limitation was from the deaths of a few shellfish from each species before they could be measured again. These individuals were removed from the data sheet because their change in growth could not be calculated; however, this changed the sample sizes of each species and for each treatment. In addition to sample sizes, the measured values for length, width, and depth could have error due to some of the digital calipers breaking during the experiment. A limitation not related to experimental data collection but rather with design would be that this study was conducted within a lab to have controlled conditions instead of being conducted in the species' wild habitat. There could be other factors not accounted for in the lab that would influence shellfish growth in the wild.

Despite these limitations, the results found from this study are vital to the overall goal this study is a part of. The growth of shellfish between species and treatments will help researchers and management understand how the effects of climate change are affecting commercially important shellfish. This understanding will be helpful for developing management strategies for shellfish harvesting and aquaculture. Continued research is also important to further understand the species-species differences in growth which there is a lack in collective research on.

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