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Assessing the Habitat Suitability of Plankton in the California Current System under Changing Oceanic Conditions

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ABSTRACT: Increased atmospheric carbon dioxide (CO_2) concentrations are causing unprecedented changes in global oceanic properties. Global trends demonstrate acidification of waters, rising temperatures, deoxygenation, and decreasing aragonite saturation states. Evidence suggests that changes in chemical and physical oceanic properties will constrain the habitat of marine organisms, particularly planktonic species inhabiting upper surface and subsurface waters down to 300-500 m (Antell et al. 2021). As plankton serve as the base of the aquatic food chain, shifts in planktonic composition and habitat are likely to have wider impacts on the marine ecosystem (Winder & Sommer 2012). This study maps planktonic communities against relevant environmental gradients using physical, chemical, and biological data from the 2021 NOAA West Coast Ocean Acidification cruise conducted along the California Current Ecosystem (CCE). While many studies have analyzed the impact of individual environmental drivers, fewer have determined how multiple stressors act together to limit the habitat suitability of marine organisms. In addition to studying general planktonic community structure, we will construct a habitat suitability index to assess how different environmental parameters act together to constrain the habitat of Dungeness crab (*Metacarcinus magister*) larvae. This concept leads to the Habitat Suitability Web-Based App which allows the user to create a mock threshold for any marine species and visualize the habitat; the outputs are a map and table that are manipulated by 5 different abiotic factors like depth and pH. Ultimately, our team will use a multi-stressor framework to determine the effects of changing oceanic physicochemical properties on Dungeness crab larvae and other planktonic communities. Planktonic species act as the base of marine ecosystems and West Coast fisheries; thus, it is essential to understand how intensified ocean warming and acidification will constrict the habitat of planktonic communities. Moreover, the communication of this information to stakeholders outside of the scientific community is essential for the implementation of effective mitigation and adaptation strategies. For this work to have a more widespread impact, those without a scientific background must be able to easily understand the main takeaways of our research. In order to achieve this, our team utilized several methods of outreach in order for our science to be most effective.

1. INTRODUCTION

Over the past few decades, rising anthropogenic carbon dioxide (CO_2) emissions have increased atmospheric CO_2 levels. Increased atmospheric CO_2 concentrations change oceanic properties, including rising temperatures, deoxygenation, and a reduction in seawater pH through a process known as ocean acidification (Talley et al., 2015). Given that planktonic organisms are adapted to specific biogeochemical and physical conditions, changes in oceanic properties can constrain the habitat of affected species and alter planktonic community compositions (Valiela, 2016). Ocean acidification and decreasing calcium carbonate saturation states are particularly relevant to planktonic species. Calcium carbonate serves as the main building block for many calcifying planktonic organisms and undersaturated conditions lead to reduced calcification and growth rate of planktonic organisms (Sampaio and Rosa, 2019). The California Current System (CSS), a region high in biodiversity, is currently undergoing changes in oceanic properties as a result of anthropogenic CO_2 emissions (Siedlecki et al., 2020). While past research suggests that ocean changing oceanic conditions are expected to impact the habitat of planktonic species, specific impacts on planktonic communities remain to be found in the CCS (Valiela, 2016).

Our practicum team is assisting the National Oceanic and Atmospheric Administration (NOAA) in understanding the ecological impacts of climate change off the North American West Coast. Throughout our project, we aim to find the answer to the following questions: What are marine organisms' biological and ecological responses to environmental gradients in the CCS? How do biogeophysical parameters and their climate-change related changes in the CCS constrain the habitat of calcifying organisms in the current ocean? What approaches can be practical and effective for changing public perception of ocean acidification? How can we adapt an existing habitat sustainability model with multiple parameters to create a habitat suitability index (HSI) for other species?

In order to gain a better understanding of the threat to our coastal environments and to explain observed biological patterns and responses to climate change, our team conducted analyses of physical, chemical, and biological data from the NOAA cruises project. We created a taxonomic dataset of planktonic community structure from water samples and explored how current environmental gradients affect the community structure at three regions in the CCS through statistical analyses. Using these same databases, our team produced an HSI for *M. magister* (more commonly known as Dungeness crab) during its megalope stage, at which it is a calcifying planktonic organism. Our HSI is based on an HSI for *Limacina helicina* produced by Bednaršek et al. (2022). *L. helicina* are a dominant pteropod species found in the CCS and similar to *M. magister* larvae, are calcifying planktonic organisms (Bednaršek et al. 2022). Using our Dungeness crab as a basis, we also created a web-based habitat suitability app (HSI app) where users can put their data in and create a spatial scale map. Using the HSI model, we can predict the sustainability of marine organisms. Our HSI model and accompanying web-based app will provide future researchers with open availability to explore aquatic organisms' habitat sustainability in the CCS. This model can also provide versatility where researchers can take a similar approach and observe the sustainability of other organisms.

In addition, we will use a variety of communication and outreach methods to ensure that this information is available and comprehensible to shareholders. This will be done so our team can eliminate a "language barrier" to ensure that effective mitigation and adaptation strategies for the California Current System are implemented. The main methods of outreach have been conducting in-person events, managing a website, creating blogs, and posting updates on social media accounts. All of the communication efforts were crafted in a way that could explain complicated scientific concepts in a digestible way to the general public.

2. MATERIALS AND METHODS

2A. Utilization of the Planktoscope

2A.1 Plankton Identification

In 2021, NOAA conducted their West Coast Ocean Acidification (WCOA) cruise, which collected carbonate chemistry data along the CCS. The cruise runs from Vancouver Island in Canada to Southern California (Figure 26). The WCOA Cruise collected water samples via Niskin bottles at 31 stations along 17 transect lines during June and July 2021. The water samples were then analyzed using a PlanktoScope, a microscopic camera device capable of taking images of plankton. The 2021 WCOA cruise water samples resulted in a total of 854,352 images, which were then uploaded to a web platform called EcoTaxa. Using EcoTaxa, we sorted them into taxonomic or morphologic categories with the help of a machine learning algorithm. Images were filtered using geographic coordinates to focus on specific sampling stations. Descriptive categories, such as detritus and bubbles, were used to sort out non-living artifacts. Living organisms were sorted into the lowest taxonomic groups possible.

Due to the large number of images to be identified via EcoTaxa and our limited time frame, we decided to focus our analyses on 3 regions called Transects 2, 5, and 8 and thus only validated images from sampling stations within those areas. Each transect has only two or three sampling stations at which the PlanktoScope took images. We differentiated between these stations by labeling each station as either nearshore or offshore, allowing us to describe differences in nearshore and offshore environmental parameters and community structures. Transect 2 is near Vancouver Island in Canada, is referred to as Barkley Sound, and includes three stations: station BS6 (48.8115°N by 125°W), which we have categorized as the nearshore station, BS14 (48.7186°N by 125.677°W), the intermediate station for this transect, and BS64 (48.1847°N by 126.5976°W), the offshore station. Transect 5 is at the mouth of the Columbia River near the U.S. Washington and Oregon border and is referred to as the Columbia River transect. It includes three stations at which biological water samples were taken. The nearshore station is called CR24 (46°N by 124°W), the intermediate station is CM5 (45.9233°N by 124.0832°W), and the offshore station is CR40 (46.1298°N by -124.91°W). Transect 8 is near the U.S. California and Oregon border and is referred to as Brookings. It has one nearshore station, FKC (41.5982°N by 124.1782°W), and one offshore station, B66 (41.7169°N by -125.6568°W). The method of validating all images within a transect was chosen in order to have data that is more consistent and complete in comparison to a method of only validating a representative sample of the images within a transect. This process also allowed for more thorough analyses later in the project.

2A.2 Biophysical Data Visualizations

In order to begin analyzing how environmental gradients affect planktonic community structure, we first used section plots provided by Dr. Maxence Guillermic that visualize 8 variables across the CCS down to a depth of 150 meters in order to take note of regions with significant gradients. From these observations, we narrowed our potential regions of interest from 17 transects to 9 transects. We then used the software Ocean Data View (ODV) to visualize the biogeochemical and physical properties of the water in the CCS. Planktonic samples were collected very close to the surface, at about 1 meter depth, so we chose to use the shallowest depth of physical and biogeochemical measurements to create nearshore to offshore plots. We visualized the entire CCS for 10 different variables including ammonia, carbonate, phosphate, Chlorophyll A, salinity, temperature, dissolved inorganic carbon (DIC), nitrate, oxygen, and pH. We then visualized the environmental gradient for 9 specific transects with 8 different variables. Those variables are nitrate, oxygen, pH, phosphate, temperature, DIC, Chlorophyll A, and salinity. In addition, we used section plots made by Dr. Richard Feely using the software Surfer that span each transect down to 300 meters depth. These plots were used to cross reference our ODV nearshore to offshore plots as well as to inform our observations of biogeochemical gradients at each transect. We used our observations to inform our decision of which transects to focus our analyses on.

2A.3 Analyses of Biodiversity and Composition of Planktonic Communities

To determine the planktonic community composition, data on the sorted images were downloaded from EcoTaxa and analyzed via Microsoft Excel. Data from each transect was divided into the nearshore and offshore stations for ease of comparison. Unidentifiable images of plankton, detritus, and images that contained either no planktonic organism or bubbles were filtered out of the dataset, with only real taxonomic groups and names remaining. The data was summarized using a pivot table, and the count of each species in each category was determined. To measure the diversity of species in the community, a Shannon Diversity Index analysis was performed in Excel. The Shannon Diversity Index is calculated using the following equation:

$$H = -\Sigma p_i * ln(p_i) \qquad \text{(Eqn. 1)}$$

where p_i is the proportion of the entire community made up of species *i*. A higher the value of H means there is a higher diversity of species in a particular community, and a lower value of H implies a lower diversity. A value of $H = 0$ indicates that there is only one species present. Community composition was also visualized via pie charts illustrating relative abundance of major species groups for the six stations. Absolute and relative abundance, and the relative biovolume of each station were visualized via Matlab.

2A.4 Statistical Analyses

Principal Component Analyses (PCA) and Analysis of Variance (ANOVA) tests on the community structure were conducted with the data analysis software JMP®. A summary table of physical characteristics and biological abundances, collected at all seven stations across the three transects of interest (Transects 2, 5 and 8), was used as an input for the PCA in JMP. The resultant PCA was based on a correlation matrix.

2B. Development of Habitat Suitability Index (HSI) using physicochemical and biological sampling

2B.1 NOAA cruises

The NOAA WCOA cruises sampled vertical profiles of temperature, salinity, macronutrients, oxygen, chlorophyll-*a*, dissolved inorganic carbon (DIC), total alkalinity (TA), and pH in 2016 and 2021. Sampling was done along 17 cross-shelf transects in the California Current System 22 stations in 2016 and 30 stations in 2021. The NOAA WCOA cruises also conducted biological sampling at these locations. Dungeness crab larvae were collected during daytime sampling using 333 μm mesh Bongo nets with 30- to 45-minute oblique tows from 60 m depth to the surface. We assessed four different parameters: aragonite saturation state (Ω_{ar}), pH, temperature (T), and dissolved oxygen (DO). pH, T, and DO were measured directly. Ω_{ar} was calculated using the CO2SYS program outlined in Feely et al. (2016) using the program CO2SYS.

CO2SYS performs calculations relating to parameters of the CO_2 system in seawater and freshwater. The program uses two of the four measurable CO_2 systems which are TA, total inorganic CO_2, pH and partial pressure of CO_2. In this study, we used the combination of TA and total inorganic CO_2 to calculate Ω_{ar}. Beyond measurable CO_2 parameters, additional variables such as T, salinity, pressure and concentrations of phosphate, ammonium, and silicate were considered when calculating aragonite saturation. The CO2SYS program also requires the choices for dissociation constant such as K1 and K2 for carbonic acid, K_{SO4} for bisulfate ion, and pH scales. For these dissociation constant values, we referenced the values outlined in Feely et al. (2016).

Given that *M. magister* megalope are found in the upper surface waters, our HSI focuses on surface waters. Ω_{ar}, pH, T, and DO are averaged over the upper 100 m.

2B.2 Regional time series

We supplemented the WCOA cruise data with data from Juvenile Salmon and Ocean Ecosystem Survey (JSOES) off central Oregon. The JSOES provided *M. magister* presence or absence observations along with local hydrographic data for 2015 to 2018. Presence/absence samples were collected using an integrated Bongo net between 20 m and 30 m. Sampling methodologies varied between the WCOA cruises and JSOES time series. To minimize potential bias between the datasets, our HSI takes into account presence/absence data rather than abundance data. The JSOES time series did not measure all oceanic properties necessary to calculate Ω_a using methods explained in Feely et al. (2016). Instead Ω_a for the JSOES time series data was calculated using different equations as following:

$$\Omega_a = \alpha_0 + \alpha_1(O_2 - O_{2,r}) + \alpha_2(T - T_r) * (O_2 - O_{2,r}) \quad \text{(Eqn. 2) (Juranek et al. 2009)}$$

The coefficient values and constant values such as T_r and $O_{2,r}$ were obtained from the table provided by Juranek et al. (2009) and dissolved oxygen were converted from ml/L to umol/Kg using the following equations:

$$\text{DO(umol/kg)} = \frac{Oxygen\ (m/L)*44600}{(Density + 1000)} \quad \text{(Eqn. 3)}$$

After calculating Ω_{ar} using Equation 2, Ω_{ar} and T values were averaged over the upper 100 m.

2B.3 Habitat Suitability Index model development for M. magister

Using various combinations of Ω_{ar}, pH, T, and DO averaged over the upper 100 m, we generated multiple HSI models for *M. magister*. Ω_{ar} and T produced the most valid results (Table 2). Using the HSI model, we can identify the environmental conditions where a *M. magister* megalope is typically found in the CCS. Our HSI model code is based on an HSI model for *L. helicina* produced by Bednaršek et al. (2022). To generate the HSI model, we used a linear function derived from a generalized linear model. The HSI uses logit transformation, transforming the resulting linear function from an infinite scale to the index value between 0 and 1:

$$HSI = \frac{e^{LF}}{e^{LF}+1} \quad \text{(Eqn. 4) (Bednaršek et al. 2022)}$$

The HSI produces numbers between 0 and 1 with "0" indicating predicted absence and "1" indicating predicted presence. Numbers between 0 and 1 indicate probability of finding *M. magister* using the same tow protocols used on the WCOA and JSOES line research cruises.

2B.4 HSI Web-Based App

Different abiotic factors affecting the Dungeness Crab's survivability inspired an app that looks at habitat sensitivity and suitability. This web-based application is designed to interactively visualize WCOA cruise data and review the suitability of various marine species in the CCS. Users are able to input thresholds of multiple environmental parameters to produce a geographic representation of a species' HSI in the CCS. All data used by this application was obtained from the 2021 WCOA cruises.

We produced the web-based application via the R Shiny platform, using packages such as leaflet and ggplot. The application has two main outputs: a map and a table. The map shows all the stations available. The table shows all of those sites and their associated parameters. The map and table inputs are responsive to the sliders. This is best used when the user has a hypothetical threshold for a given species. The map will display the stations where the criteria made match the parameters. This is better understood with the table: “High” means the station/area is suitable for the species. “Low/ Not suitable” means that the sliders’ criteria were not able to fully match with any of the stations. The team hopes that users from any background will be able to successfully understand the several parameters that determine a habitat’s suitability for marine species on the Pacific Coast. This will encourage and educate users to understand that these variables are sensitive to phenomena like climate change.

Users can find the code and necessary files on Github:
https://github.com/fktrisha/hsi-ucla22practicum

2C. Communication and Outreach

2C.1 Website

We used the website builder Wix.com to design a website for our project (found at https://isimonito.wixsite.com/dungeness), with the purpose to communicate our research on planktonic habitat suitability in the CCS under changing oceanic conditions. We used a free website builder in order to minimize expenses for the project. In order to provide the public with an understanding of our research, the website is designed to explain the different facets of the project and get the user more interested in relevant topics related to our research. Each tab provided information on a different aspect of the project. We provided information on the background to our research, our research questions, the Habitat Suitability Index modeling and the analysis of planktonic community structure measured by Planktoscope. The content of the website was intended to be easily understood by nearly anyone who arrived at the site. With this in mind we wrote our text with a model “intended audience” of early high school students.

The website also hosts the HSI Web-Based app, allowing users to manipulate environmental variables and visualize the distribution of the planktonic Dungeness crab larvae along the California Current System. Within the app there is a “User Info” tab built in to instruct the user how to operate the app itself, as well as an explanation of the basics of the app.

The team published several blogs covering topics including background information surrounding our topic, the trajectory of our project, and previous academic studies that guided our research. These blogs were posted on the team website for public viewing. The blogs were written with the intention of being short and informative, but not too dense, in order to be more inclusive to the diversity of readers with many different background experiences with science.

Moreover, the website hosted a page dedicated to the team itself, describing each member’s interest in the project, and roles and responsibilities .

2C.2 Outreach Event

The team hosted an in-person outreach event on the UCLA campus to increase public awareness of changing oceanic conditions' impact on planktonic organisms in the CCS. This outreach event included special attention on the uniting factor of the different teams for our project, habitat suitability Dungeness Crab (including larvae in its planktonic stages). We designed a research poster describing the research our team conducted, and explaining the rationale behind our research, along with some suggestions for individual action to decrease ocean acidification and its impacts. Along with information describing the research, the poster included a QR code to a quiz hosted on the team website. The quiz aimed to increase interaction by UCLA students and staff by offering prizes, which were provided with the correct answer to the questions. The Green Initiative Fund (TGIF) at UCLA provided the funding for the prizes given to the quiz participants, two 18 Oz. Hydroflasks.

3. RESULTS

3A. Planktoscope

3A.1 Physical and Biogeochemical Gradients

Species	**Plankton Type**	**Information**
Chaetoceros	Diatoms	Chain forming, nitrogen fixing centric diatom; prefers a salinity of 19-38 psu, temperatures of -2 - 29℃, nitrate of 0.05-34 µmol/L; higher densities in cooler waters; common throughout the summer; are able to survive in nutrient-depleted waters and can bloom when nutrients are replenished (Booth et al., 2002).
Rhizosolenia	Diatoms	Long, cylindrical, straight or slightly curved diatom; found in brackish and marine waters; can form mats and migrate vertically below the euphotic zone to exploit nitrate pools (Villareal et al., 1996).
Tintinnida	Ciliates	Family; Ciliate protists attached to a lorica and shaped similarly to a bowl with a flared collar; with size ranges from 20-200 µm; phytoplankton consumers; most widely distributed in open waters and near shores, but largely absent from far northern and southern seas (Dolan et al., 2012).
Bacteriastrum	Diatoms	In the *Chaetocerotaceae* family; centric

		diatom; cells have hollow silica tubes that typically emerge in a radial pattern for the valves; widely distributed in coastal, tropical, and warm-temperate waters, with some species near Arctic and Antarctic regions (Piredda et al., 2022).
Thalassionema	Diatoms	Genus; pennate diatom with length of 10-110 µm; Found primarily in temperate to tropical waters occurring in higher concentrations in the spring (Hoppenrath et al., 2009).
Pseudo-Nitzschia	Diatoms	Genus; pennate diatom; produces toxic domoic acid blooms both offshore and in bays, which is responsible for amnesic shellfish poisoning, increase in blooms linked to ocean warming and higher nutrient amounts (Bates et al., 2018).
Undellidae	Ciliates	Family; tintinnid ciliate; shaped like a vase with three walls, with the walls becoming thinner towards the posterior lorica end; abundant in many environments (Agatha & Bartel, 2022).
Steenstrupiella	Ciliates	Genus; size is about 21-23 µm; Ciliate attached to lorica that is flared on one end; found in many marine environments and have stable communities in the ocean, but occur less in polar regions (Li et al., 2018).
Eutintinnus	Zooplankton	Genus; generally have a tapering goblet-shaped lorica that is slightly flared at one end; has been shown to increase grazing rates under elevated pCO_2 (Olson et al., 2018).
Dinophysis	Dinoflagellates	Genus; round, flat cells; size range from 30-120 µm; can form extensive blooms that can produce okadaic acid, which is part of a group of lipophilic algal toxins known as diarrhetic shellfish toxins; occur in higher concentrations during the summer (Shultz et al., 2019).
Pyrophacus	Dinoflagellates	Genus; in the *Pyrophacaceae* family; cells are nearly circular with two flagella; found mainly in tropical and subtropical waters; some

		species are bioluminescent and there is evidence that some species are sensitive to pollution (Lapota et al., 2007).
Asterionellopsis	Diatoms	Genus; the foot pole is trapezoidal with a thin region (head) extending from it that is two to four times the length of the foot pole; cells unite at the foot poles, forming star shaped (two dimensional) or spiral (three dimensional) colonies; found near cold and temperate coastal water (Franco et al., 2016)
Thalassiosira	Diatoms	Genus; centric diatom; polar waters may be barrier for growth of some species; generally verall prefers temperate to polar waters; significant components of phytoplankton blooms (Chappell et al., 2013)

Table 1: Most abundant Plankton identified in Transects 2, 5, and 8 and their descriptions.

Based on the visualizations of physical and biogeochemical data from the 2021 WCOA cruise, including the plots made with Ocean Data View and the section plots provided by Dr. Richard Feely (unpublished), we chose to narrow our analysis of the CCS to three specific regions due to their salient environmental gradients. These regions include Transects 2, 5, and 8. The following observations of physical and biogeochemical gradients are constricted to waters directly at the surface because water samples containing planktonic organisms were collected at a depth of approximately 1 meter. Values mentioned in this subsection are approximations based on the physical and biogeochemical data plotted for Transects 2, 5, and 8.

Transect 2, or Barkley Sound, was recommended for analysis by Dr. Robert Eagle as being significant for particulate inorganic matter (PIC) and chlorophyll A. Salinity is slightly lower nearshore, at approximately 30 g/kg then steadily increases to its maximum farthest offshore, of 32 g/kg. Oxygen is at its maximum closer to shore, with concentrations close to 12 mL/L, and then decreases at the offshore stations towards approximately 9.5 mL/L. Chl A is highest closest to shore at around 4.5 ug/L, with a minimum further offshore at approximately 2.5 ug/L. Nitrate is mostly constant throughout, with concentrations around 0-5 µmol/kg. Phosphate is mostly constant as well, at 0-0.5 µmol/kg. DIC is lowest at the near shore station and then increases toward the offshore station from 1825 µmol/kg to 1975 µmol/kg. pH is highest near the shore at around 8.1, and then decreases to its minimum of about 7.9 at the station furthest from shore. The temperature is highest near the shore (16 ºC) but is relatively constant throughout the transect, with slightly higher temperatures being seen at the middle stations, 15 ºC. Carbonate is highest closest to shore and decreases at the offshore stations, changing from approximately 170 µmol/kg to 140 µmol/kg.

Transect 5, the Columbia River transect, was recommended by Dr. Robert Eagle as being significant for salinity due to its proximity to a freshwater river. Salinity is lowest closest to shore and then increases drastically as you move offshore, transitioning from approximately 24 g/kg to 32 g/kg. The nearshore to offshore plots we created based off the NOAA 2021 WCOA cruise shows that this transect has relatively high oxygen throughout when compared to other locations on the West Coast. A closer look reveals that there is a hotspot of high dissolved oxygen offshore of around 8.5 mL/L, as well as a gradient of changing oxygen concentrations. There is also a highly variable carbonate gradient in which there is higher carbonate close to shore (130 µmol/kg), then a carbonate minimum of around 100 µmol/kg, and then a gradual increase to a carbonate maximum of 150 µmol/kg), then a slight decrease from that as you move offshore. Chl A concentrations show similar variability, with low concentrations nearshore, a maximum around the middle stations, and then a lower gradient offshore, going from approximately 1 ug/L to 19 ug/L to 5 ug/L, respectively. Nitrate is mostly constant, with the highest concentrations of around 5-10 µmol/kg closest to shore. DIC has its minimum near shore and its maximum further from shore at 1500 µmol/kg to 1975 µmol/kg, respectively. pH has its minimum of around 7.7 near shore but quickly increases to approximately 8 at the middle stations and only slightly decreases at the offshore station. Phosphate is relatively constant throughout, with a value of 0.5 µmol/kg. The highest temperatures are right by the shore at 20 ºC, and the coolest temperature is farthest offshore at 16.5 ºC.

Transect 8, the Brookings transect, was recommended by Dr. Nina Bednarsek as being significant for pH. Oxygen is high near the shore, then decreases away from the shore from 12 mL/L to 9 mL/L. Nitrate is lower near the shore at 1 µmol/kg, then increases to 12 µmol/kg, and decreases again until it reaches 1 µmol/kg once again at the station farthest from shore. Similarly, phosphate is lower near the shore at 0.4 µmol/kg, then increases to its highest measurement of 1.2 µmol/kg near the middle of the transect, but then is low again at the furthest station, decreasing to approximately 0.5 µmol/kg. Chl A is high near shore at 14 ug/L, then decreases until its minimum of almost 0 ug/L at the second to last station, but then sharply increases to a maximum at the station furthest from shore to 16 ug/L. DIC is low near the shore at 1990 µmol/kg, increases near the middle stations to 2075 µmol/kg, and has its minimum at the furthest station: 2000 µmol/kg. Similarly, pH is highest near the shore at 8, then decreases to 7.8, but then is high once again at the furthest station at 7.9. Carbonate has its maximum closest to shore, with concentrations nearing 200 µmol/kg, and then steadily decreases, but then increases slightly at the furthest station, with concentrations nearing 150 µmol/kg. The temperature is approximately 13 ℃ closest to shore, then decreases to 11.5 ºC, but then increases to its highest temperature at the station that is furthest out to sea to around 14.8 ºC. Salinity is highest near the shore, then steadily decreases until it reaches a minimum furthest out to sea, from 33.4 g/kg to 32.3 g/kg.

3A.2 Barkley Sound Transect 2

The planktonic community structure of Transect 2 changes dramatically from nearshore to offshore. The nearshore community is dominated heavily by *Chaetoceros*, with much of the remaining plankton belonging to *Rhizosolenia*. At the furthest offshore sampling station, however, *Rhizosolenia* accounts for more than 75% of the individuals observed. This structural shift is accompanied by a marked decrease in the Shannon Diversity Index (SDI) moving from nearshore to offshore, with the nearshore, intermediate, and offshores stations having SDI values of 1.107162452, 1.042714835, and 0.9434017322, respectively. The abundance of *Rhizosolenia* seems to fluctuate along with the concentrations of ammonia, nitrate, and phosphate, which are high at the nearshore station, rise slightly at the next, and then drop significantly at the offshore station. This trend is not surprising because these three compounds are nutrients necessary for *Rhizosolenia* growth. In contrast, *Rhizosolenia* seems to exhibit a reverse abundance pattern to carbonate, oxygen, and pH, which start with low concentrations nearshore, drop slightly, and then rise offshore. There is a statistically significant inverse correlation between *Rhizosolenia* abundance and carbonate concentration ($p = 0.0445$). While this is an interesting trend, the lack of statistical power in this regression precludes any certainty of the relationship.

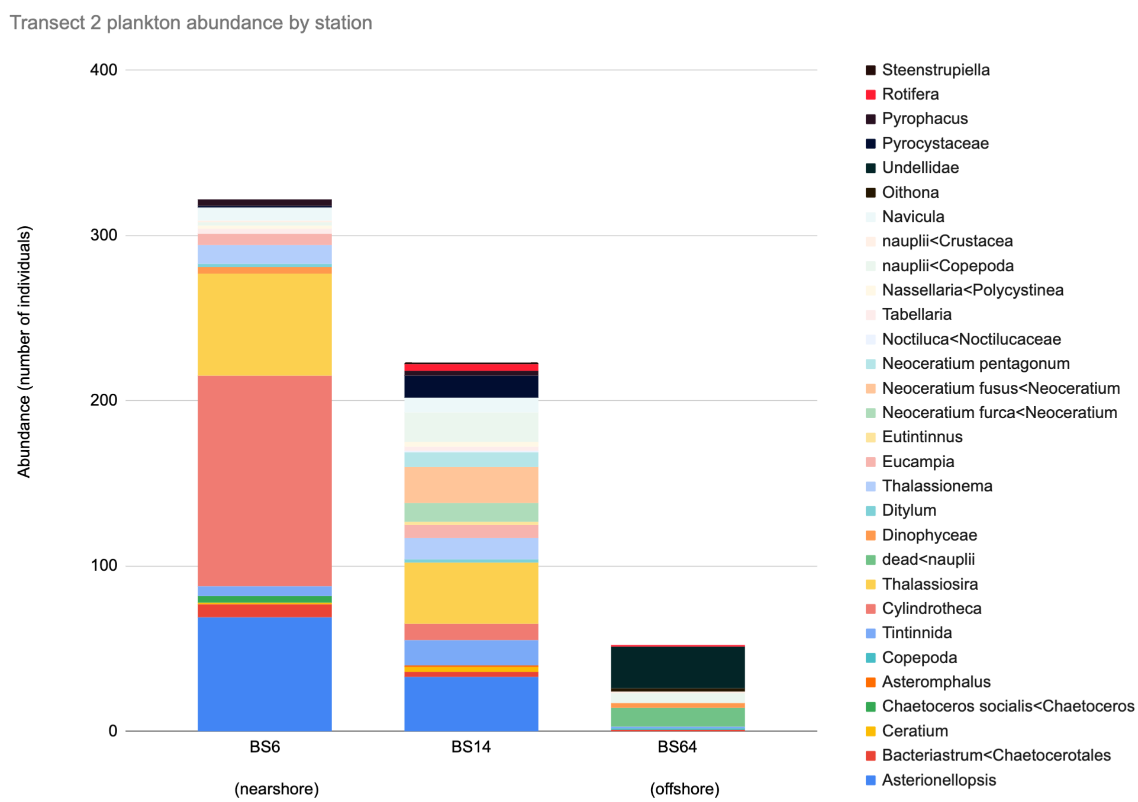

Figure 1. Absolute abundance of planktonic organisms identified at each of the three sampling stations in Transect 2. Rhizosolenia and Chaetoceros<Chaetocerotales have been omitted due to their overwhelming abundance. See **Figure 4** for the abundance of these groups.

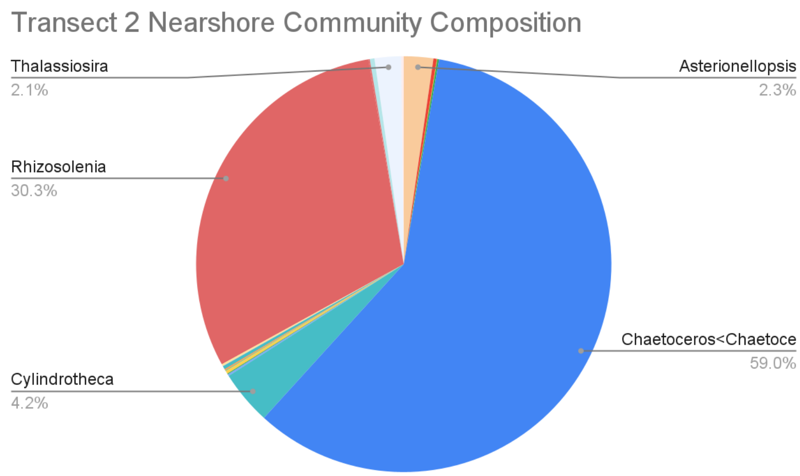

Figure 2. Relative abundance of all living organisms sampled and identified at station BS6 in Transect 2.

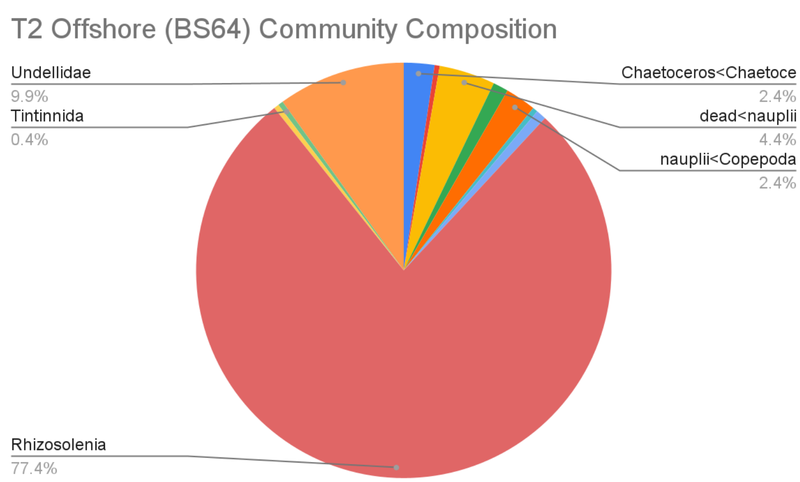

Figure 3. Relative abundance of all organisms sampled and identified at station BS64 in Transect 2.

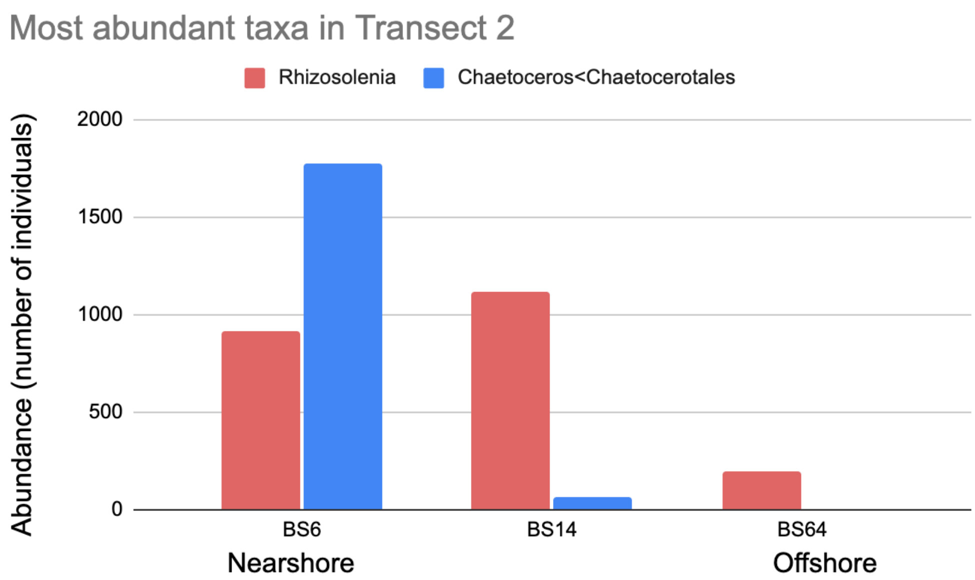

Figure 4. Absolute abundance of *Rhizosolenia* and *Chaetoceros* individuals identified across Transect 2.

3A.3 Columbia River Transect 5

Transect 5 contains two stations at which biological data was collected. The nearshore station is CR24 and the offshore station is CR40. The Shannon Diversity Index for Transect 5's nearshore station is 0.3461354122. The Shannon Diversity Index for Transect 5's offshore station is 1.194912456. This means there is a higher species diversity offshore than there is nearshore. This may be due to the significant salinity gradient in which salinity is lower nearshore and increases to its maximum offshore, as marine plankton species are often adapted to high salinity values and may be constrained by the freshwater input by the Columbia River. There is also a greater abundance of plankton at the offshore station, as shown in Figure 5. *Rhizosolenia*, a genus of nitrogen fixing diatoms, is the most abundant group in both the nearshore and offshore station (Figures 6 & 7), making up 95.2% of the planktonic community at the nearshore station and 73% at the offshore station. *Rhizosolenia* are more abundant at the nearshore station in terms of both absolute and relative abundance (Figure 8). The principal component analysis (PCA) shows that *Rhizosolenia* abundance may be correlated with nitrite and ammonia concentrations, which is consistent with *Rhizosolenia*'s role as a nitrogen fixer. The concentration of nitrate is slightly higher at the nearshore station versus the offshore station where nitrate is lower. Copepod nauplii, the larval form of copepods, and a type of mesozooplankton, are the next most abundant group at the offshore station, making up 11.9% of the community.

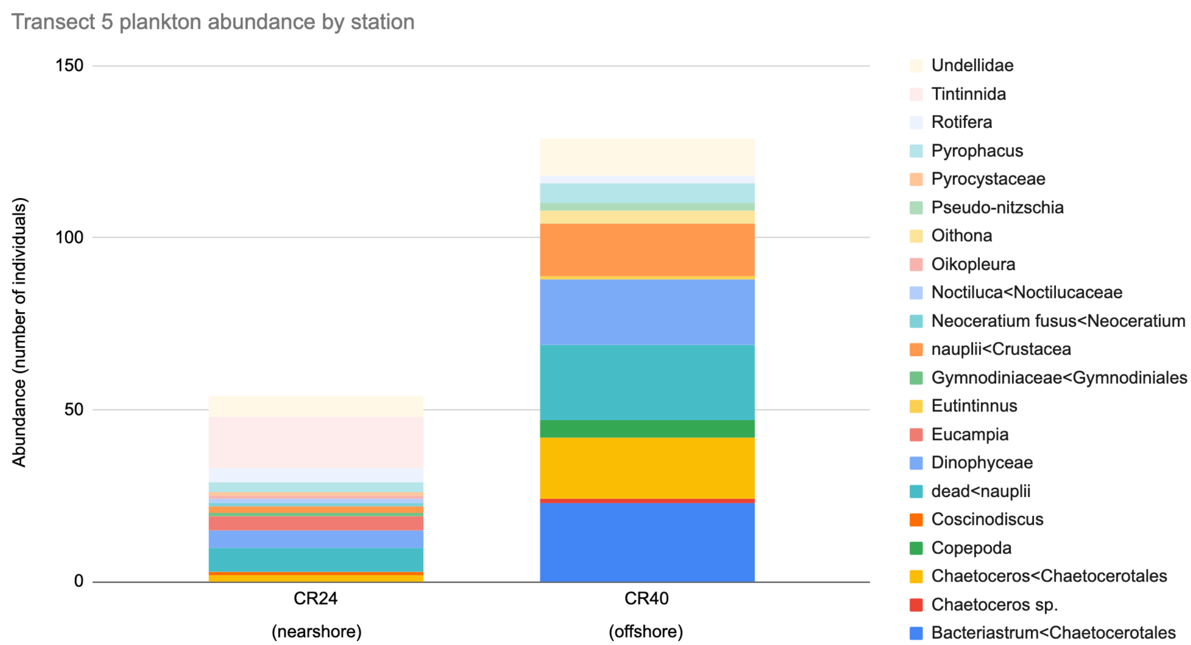

Figure 5. Absolute abundance of planktonic organisms identified at each of the two sampling stations in Transect 5. Rhizosolenia has been omitted due to its overwhelming abundance. See **Figure 8** for the abundance of this group.

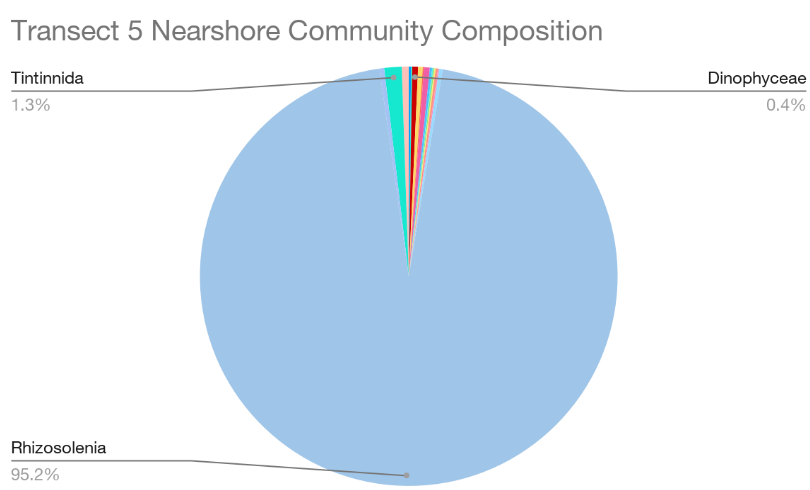

Figure 6. Relative abundance of all organisms sampled and identified at station CR24 in Transect 5.

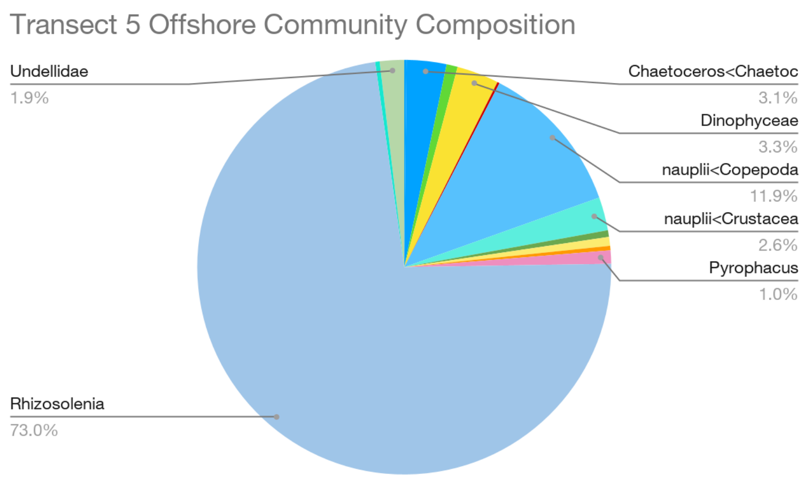

Figure 7. Relative abundance of all organisms sampled and identified at station CR40 in Transect 5.

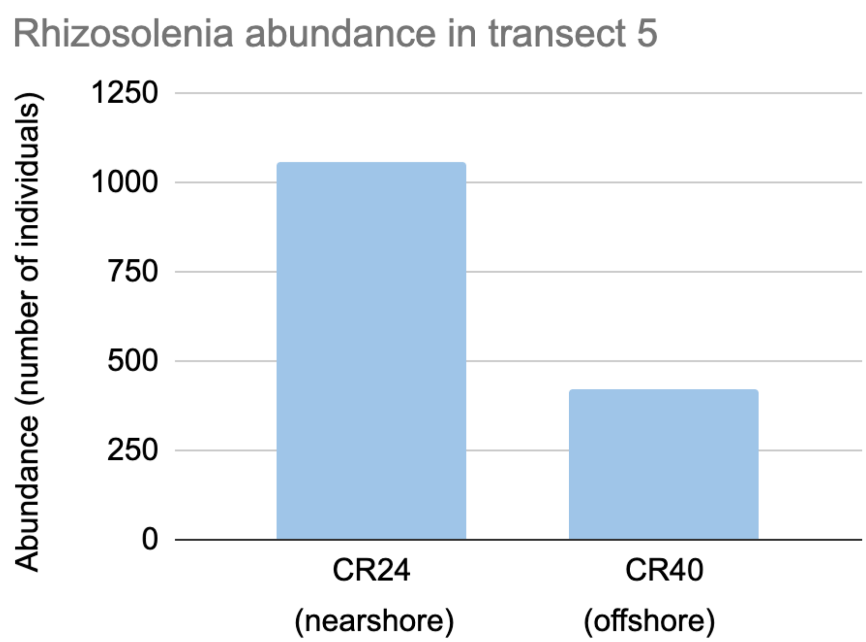

Figure 8. Absolute abundance of *Rhizosolenia* at stations CR24 and CR40 in Transect 5.

3A.4 Brookings Transect 8

Transect 8 consists of two stations: FKC (the nearshore station) and B66 (the offshore station). The nearshore station of Transect 8 consisted of 2251 organisms spread across 29 identifiable species categories after the removal of unidentifiable images. The SDI value was 1.175127901. The highest number of plankton gathered from this station were *Chaetoceros*, with 1650 images categorized, followed by *Rhizosolenia*, with 178 images, making up 73.3% and 7.9% of the community composition, respectively. For the offshore station, the SDI value was 1.534390047, meaning that this station had more species diversity than the nearshore station. The highest number of plankton gathered from this station were *Rhizosolenia*, with 1548 images categorized as such, followed by *Tintinnida*, with 171 images categorized as such out of 2400 total images in this transect, making up 64.5% and 7.1%, respectively. As seen in Figure 12, focusing on the most abundant taxa in Transect 8 overall, the population of *Rhizosolenia* increases from nearshore to offshore. Conversely, *Chaetoceros* decreases from nearshore to offshore.

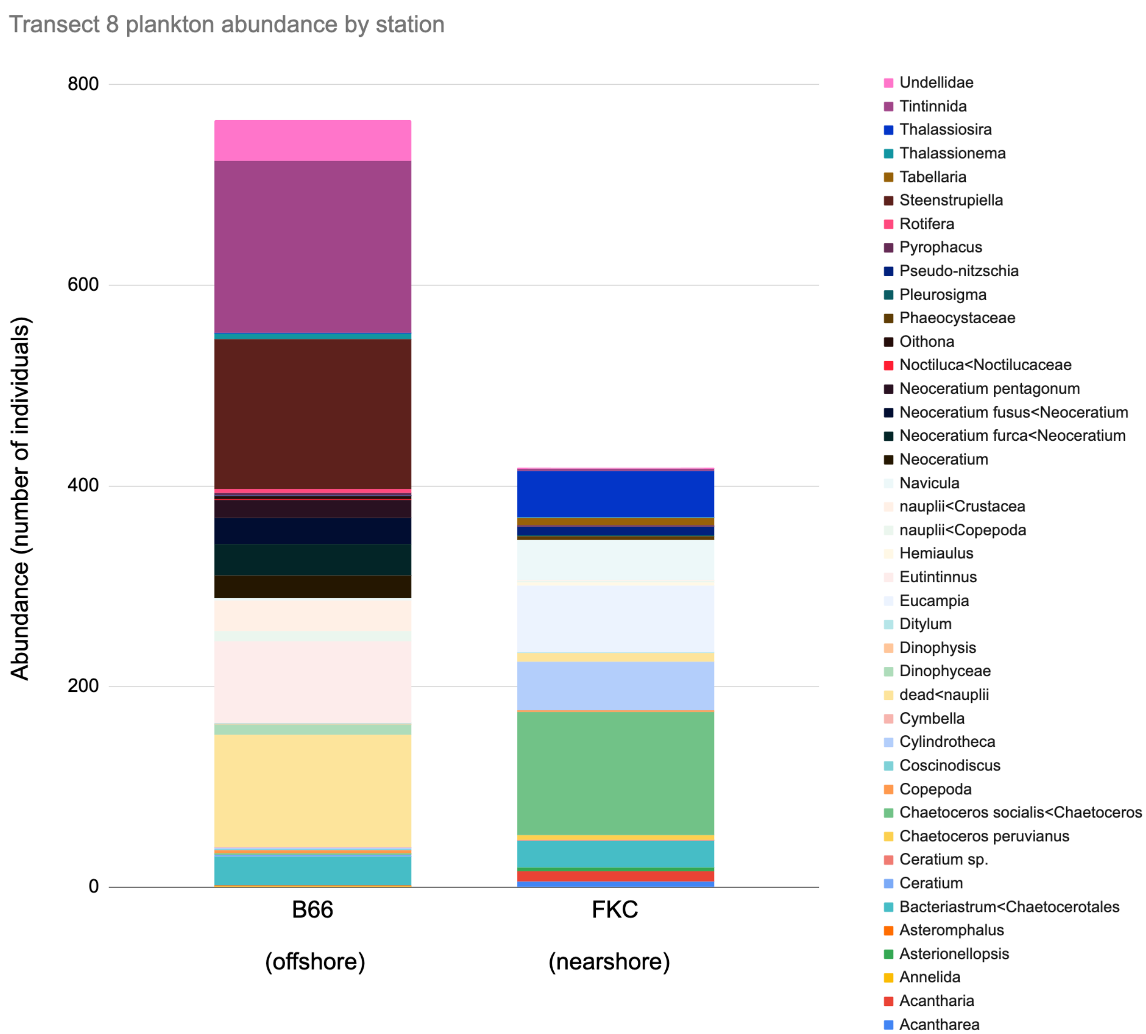

Figure 9. Absolute abundance of planktonic organisms identified at each of the two sampling stations in Transect 8. Rhizosolenia and Chaetoceros<Chaetocerotales have been omitted due to their overwhelming abundance. See **Figure 12** for the abundance of these groups.

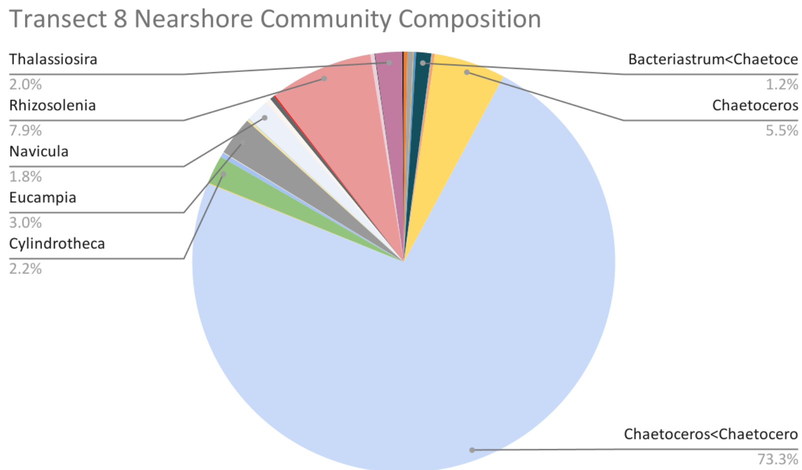

Figure 10. Relative abundance of all organisms sampled and identified at station FKC in Transect 8.

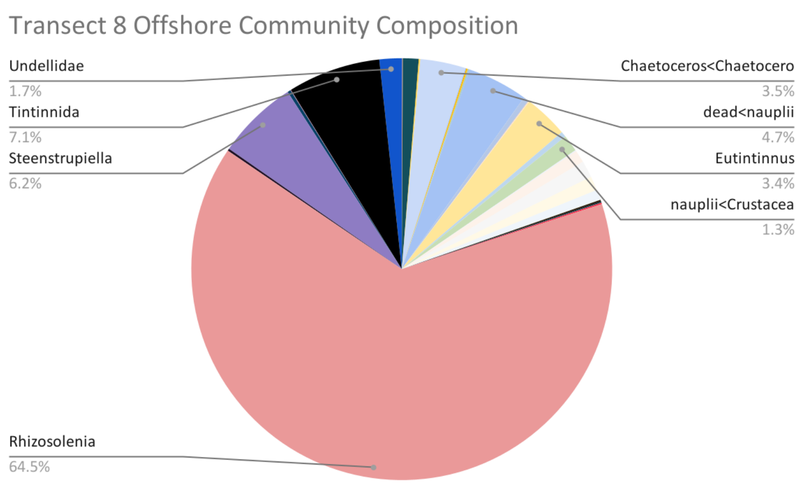

Figure 11. Relative abundance of all organisms sampled and identified at station B66 in Transect 8.

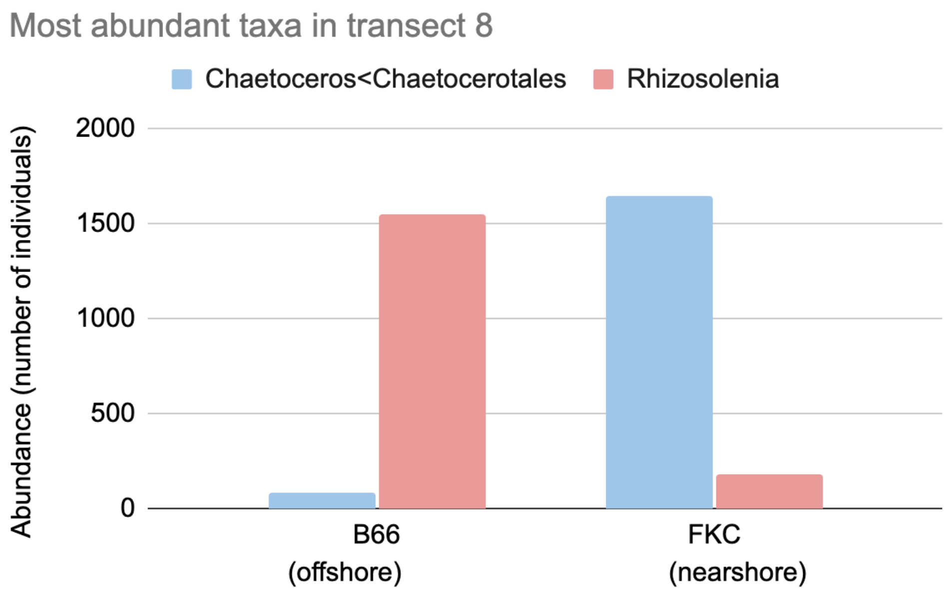

Figure 12. Absolute abundance of the two most abundant taxa, *Chaetoceros* and *Rhizosolenia*, at stations B66 and FKC.

3A.5 Statistical Analyses

As well as examining the planktonic community dynamics within these three transects, we analyzed the data from all of our sampling stations together to determine if there are broader patterns at play spanning the California Current System. We found that *Bacteriastrum* abundance increases with the Shannon Diversity Index ($p = 0.0441$). We also found that *Thalassionema* abundance increases with ammonia concentration ($p = 0.0047$). We determined that *Pseudo-Nitzschia* abundance was closely linked with several ocean chemistry gradients; *their* numbers increased along with water temperature ($p = 0.0424$) and decreased in conjunction with phosphate ($p = 0.0258$) and silicate concentration ($p = 0.0163$). While these results are promising and certainly merit further investigation, we cannot be confident of the relationships because of our low statistical power resulting from only having seven sampling stations.

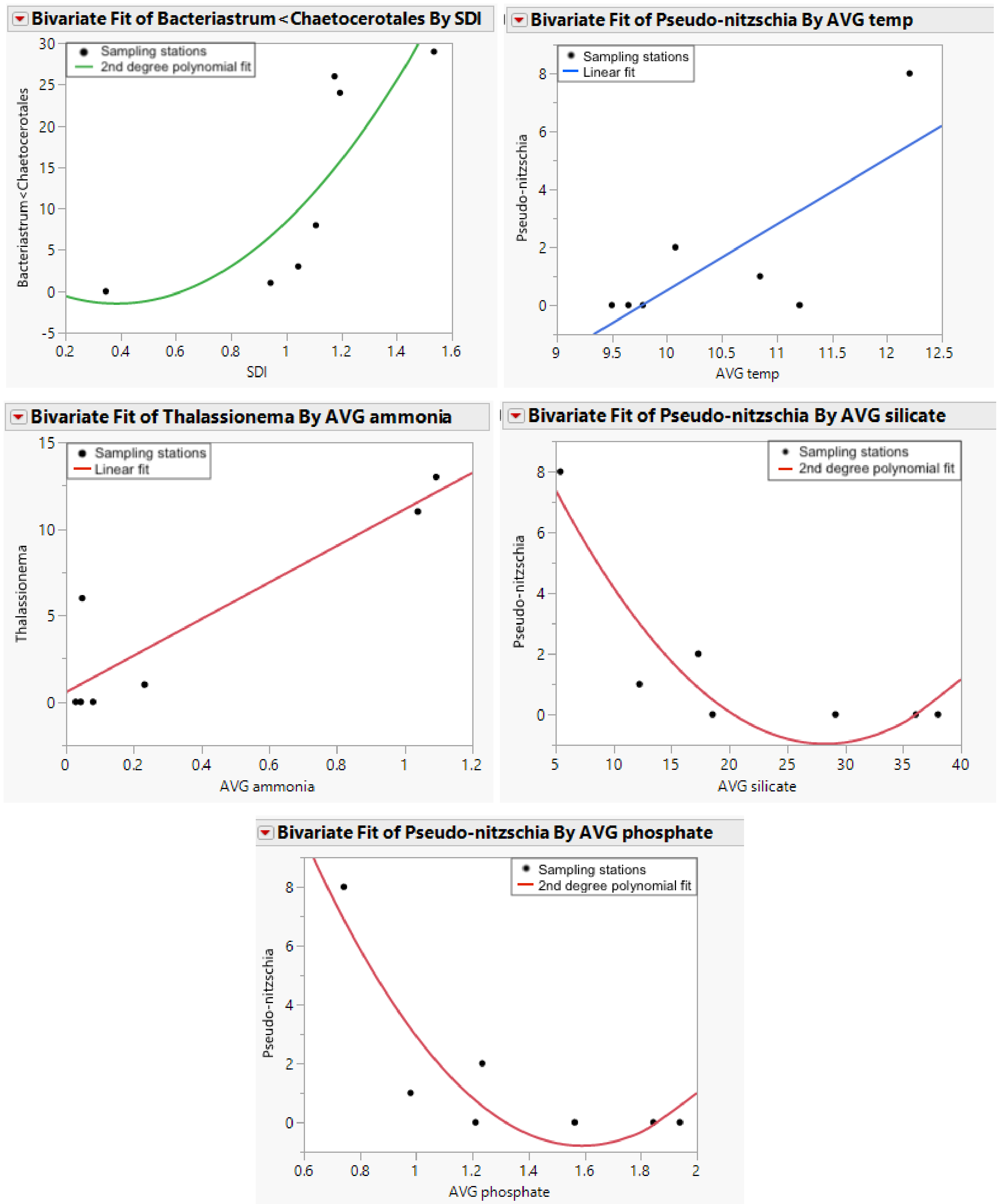

Figure 13. These plots are organized by sampling station and depict physical parameters averaged across the first 300m of the water column. Planktonic abundance is based on the total number of individuals identified.

Moreover, the Principal Component Analysis (PCA) of the physical characteristics at all transects overlaid with the planktonic community makeup provided an overview of the relationships between physical characteristics and the biological within the California Current System. Several physical characteristics showed strong correlations with each other as seen in Figure 14. The most notable correlations are seen between Phosphate, Nitrate and Silicate; Ammonia and Nitrite; as well as Temperature and Salinity.

Interesting correlations between physical components of the California Current System and biological abundances were illustrated by the PCA. Several taxonomic groups were closely correlated with the average SDI, showing a relation between overall planktonic community diversity and particular taxonomic group abundance. The ciliates *Undellidae* and *Steenstrupiella*, the zooplankton *Eutintinnus*, and the dinoflagellate *Dinophysis* show a positive correlation between their abundance and the overall diversity of the planktonic community. The abundance of the dinoflagellate *Pyrocystaceae* showed a strong correlation with nutrient characteristics of Nitrate, Silicate and Phosphate.

Several diatom groups displayed a relationship with the ocean nitrogen cycle, with strong correlation between their abundances and the nitrite and ammonia physical variables. *Rhizosolenia*, *Thalassionema*, *Asterionellopsis* and *Thalassiosira* showed a correlation with nitrate and ammonia.

Although other parameters also showed correlations between physical characteristics of the CCS and planktonic species distribution (Figure 14), these relationships were not able to be adequately explored within the timeframe of this project.

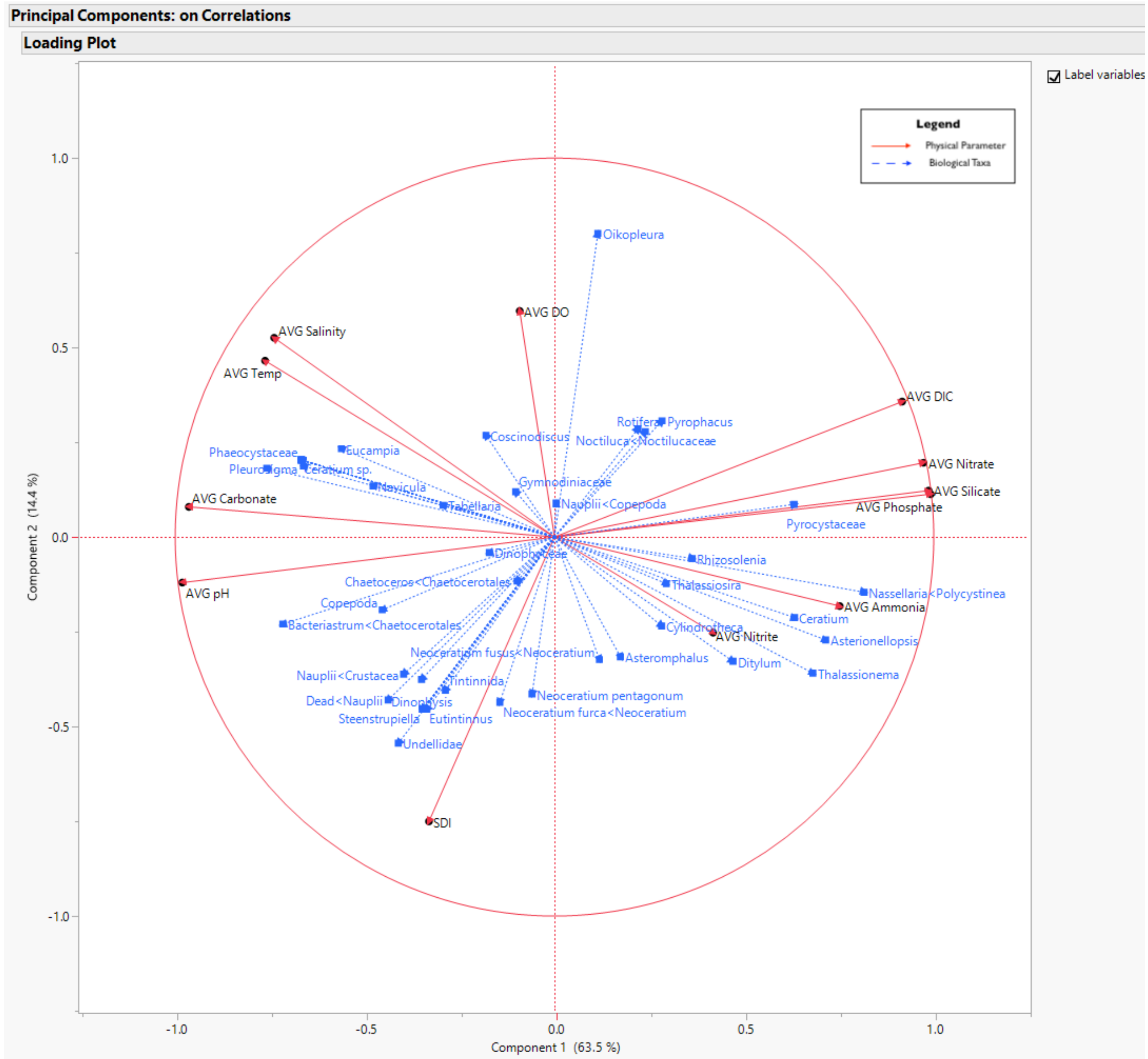

Figure 14. Principal Component Analysis illustrating the correlations between physical and biological characteristics in the CCS.

3B. Habitat Suitability Index (HSI) Model

3B.1 Temporal changes in M. magister distribution in the CCS

The WCOA dataset from 2016 and 2021 shows that *M. magister* presence is temperature-dependent. We recognize the realized thermal habitat range for *M. magister* (averaged over the upper 100 m) to be approximately 9–12°C, with peak abundances around 10°C. Using the 2016 and 2021 WCOA data the average temperature at which this species was present was approximately 10.5°C. When the temperature in the CCS was above 12°C, *M. magister* was largely absent, likely indicating a thermal maximum. With respect to Ω_{ar}, the

WCOA cruises only observed Ω_{ar}>1 when Ω_{ar} was averaged over the upper 100 m. Given these observations, we were unable to determine thresholds for *M. magister* with respect to Ω_{ar} .

3B.2 Empirical HSI predicts presence/absence from seawater properties

The empirical HSI with the combination of T and Ω_{ar} was fit to the 2016 and 2021 WCOA observations. The linear function for the empirical HSI model was as follows:

$$LF=9.5036-1.2228T+2.1642\Omega_{a} \qquad \text{(Eqn. 5)}$$

This linear function gave the strongest HSI model to explain *M. magister* presence and absence in the CCS; however, we also explored the impacts of potential combinations of physical and biogeochemical parameters on the larvae through alternative HSIs (Table 2).

We used "Skill Improvement" (SI) to validate our findings. This validation metric was based on Bednaršek et al. 2022. For this method of validation, we use a constant probability model which assumes that Dungeness crab larvae presence in net tows does not depend on the environmental conditions. SI is the difference between this constant probability and a hypothetical perfect model that only makes correct predictions of Dungeness crab larvae presence based on the environmental conditions. Higher SI values, which are expressed in percentages, suggest that the HSI model is more skillful at predicting the probability of finding Dungeness crab larvae.

The SI for the HSI with the combination of T and Ω_{ar} based on WCOA data from 2016 and 2021 is 24.5%. SI values for combinations of additional environmental parameters can be found in Table 2.

We also produced various HSIs using data from the JSOES time series. JSOES presence/absence observations did not produce valid HSI results as p-values were significantly high compared to the empirical HSI fit to WCOA data as we can see from Table 3 and figure 25 on appendix.

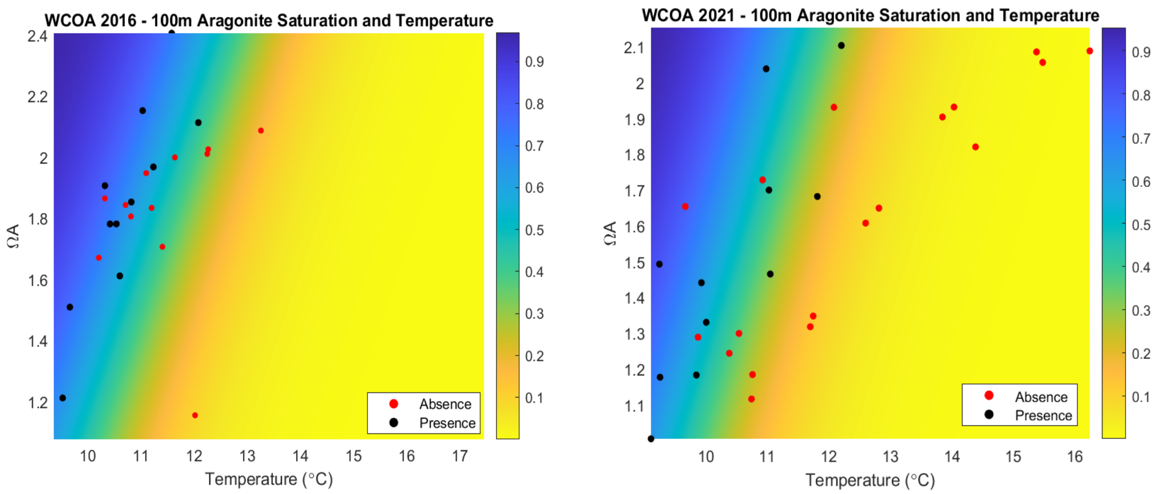

Figure 15. HSIs for *M. magister* using the combination of Ω_a and T. Predictions (background gradient) use WCOA 2016 and 2021 data while presence/absence observations (scatter plot) are split as 2016 data (left) and 2021 data (right).

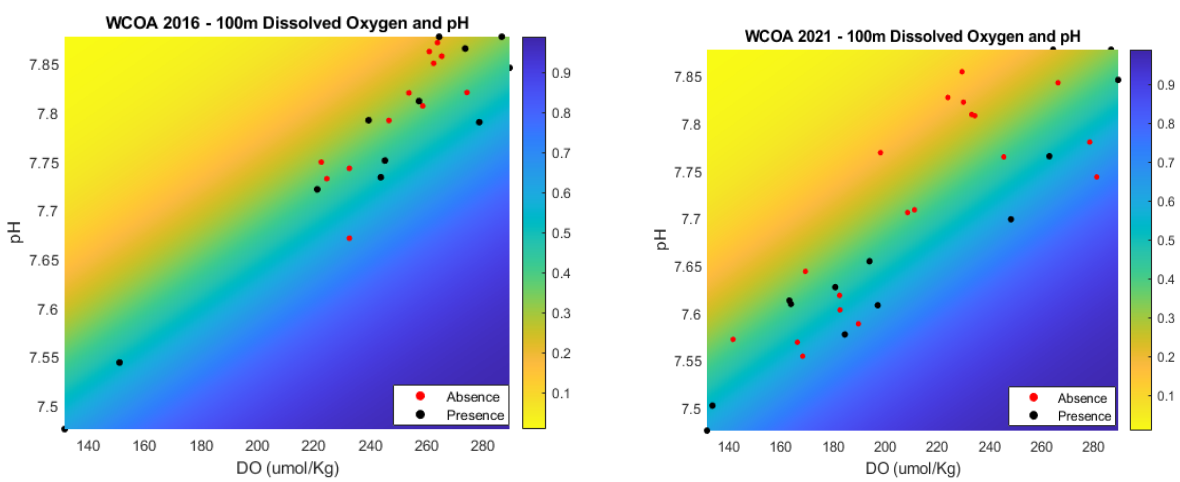

Figure 16. HSIs for *M. magister* using the combination of DO and pH. Predictions (background gradient) use WCOA 2016 and 2021 data while presence/absence observations (scatter plot) are split as 2016 data (left) and 2021 data (right).

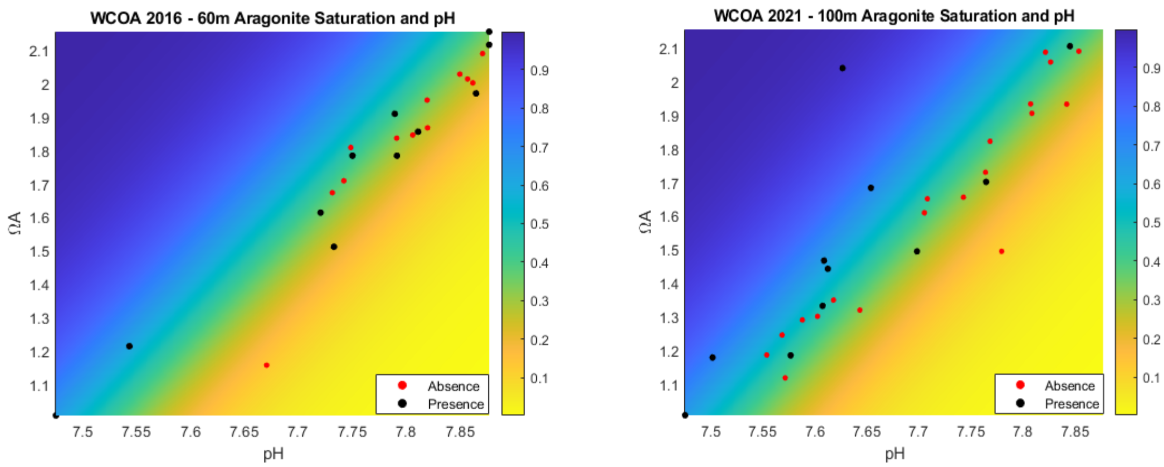

Figure 17. HSIs for *M. magister* using the combination of Ω_a and pH. Predictions (background gradient) use WCOA 2016 and 2021 data while presence/absence observations (scatter plot) are split as 2016 data (left) and 2021 data (right).

3B.3 Comparing the L. helicina HSI to the M. magister HSI

To analyze differences in *L. helicina* suitability and *M. magister* suitability, we compared the empirical HSIs of the two species. The pteropod HSI was based on WCOA observations, with the linear function as follows:

$$LF=13.49-2.475T+10.10\Omega_a \qquad \text{(Eqn. 6) (Bednaršek et al. 2022)}$$

The overall SI for the *L. helicina* model was 55%, estimated by averaging the values for the related models obtained from 2016 (tested on 2011 and 2013 data) and 2011 (tested on 2013 and 2016 data). The SI for the 2011-trained model was 70%, while the SI for the 2016-trained model was 39%.

To compare the overall habitat suitability between *L. helicina* and *M. magister,* we generated the three-dimensional regional oceanic model with the help from Dr.Faycal Kessouri, a Senior Scientist at the Southern California Coastal Water Research Project. These 3 dimensional modeling systems (Renault et al., 2021) coupled online to the biogeochemical elemental cycling model (Deutsch et al., 2021) which were forced by the atmospheric model WRF (Renault et al., 2021). The model has been set to study ocean productivity, and acidification and hypoxia regimes in the US west coast (Kessouri et al., 2020).

Using this 3 dimensional modeling system, we derived the comparison habitat suitability diagram between *L. helicina* and *M. magister* under 5m, 50m and 100m depth.

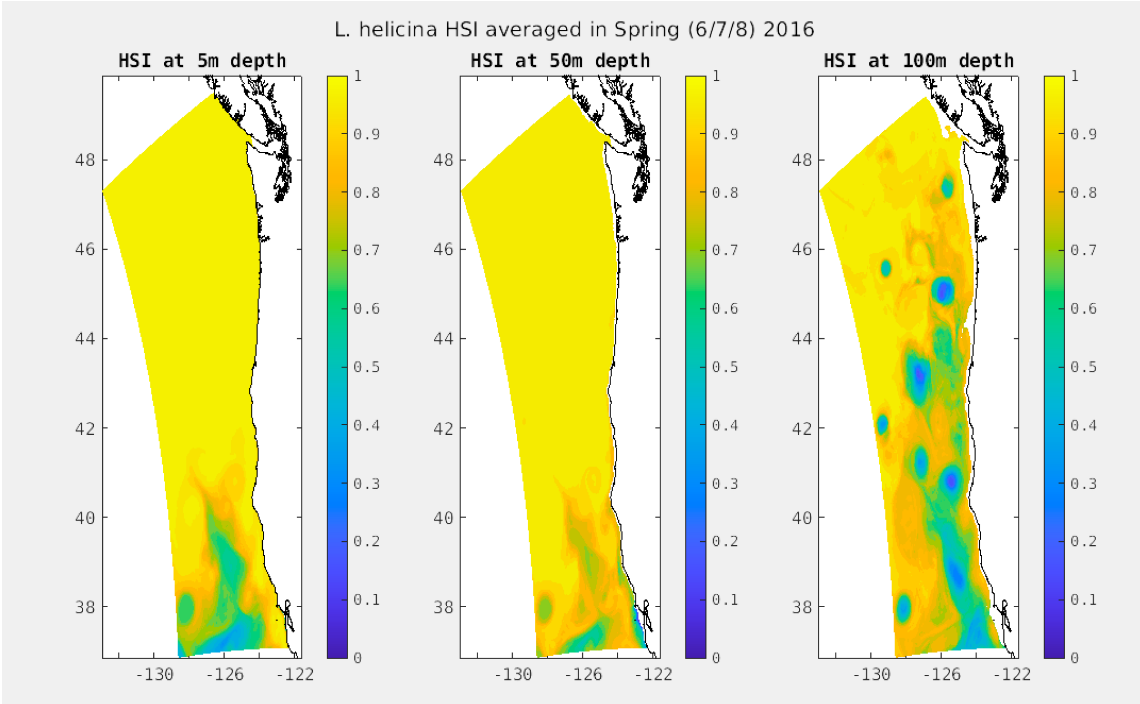

Figure 18: 3-Dimensional regional Coastal Modeling System for *L. helicina*.

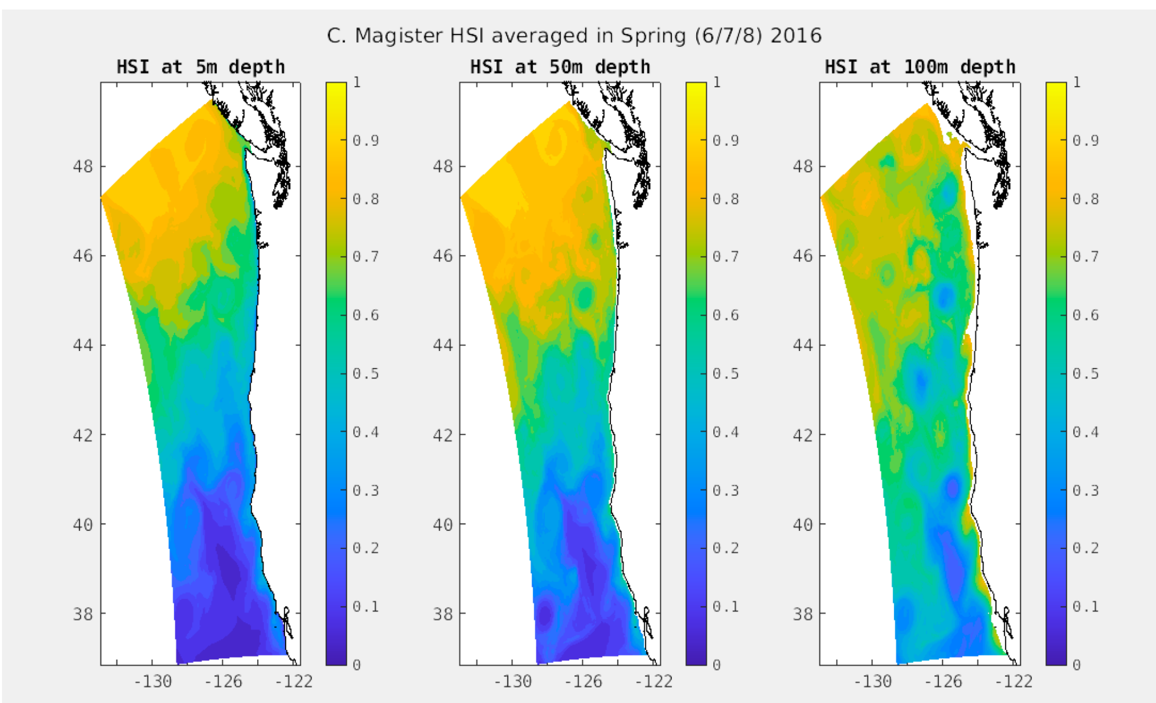

Figure 19: 3-Dimensional regional Coastal Modeling System for *M. magister.*

3B.4 HSI Web-Based App Further Details and Limitations

Details about the app are found in the User Guide tab. It highlights what data was used, how to use the application, a sample threshold for the Dungeness crab, and background information about the parameters (Figure 20). The five main parameters chosen for the application were: depth, temperature, pH, aragonite saturation, and dissolved oxygen (as shown in Figure 21). They were specifically chosen because there are key factors that influence an environment and they were considered when running HSI with the Dungeness crab. The table features each station at different parameters and the application runs a matching code to determine the suitability deemed by the user. The table features more parameters that are associated with each point: salinity, sigma, DIC, and total alkalinity (Figure 22).

The limitation of this application is the depth parameter. The map does not visualize the depth factor because it is an aerial view of the stations. The depth tells users where the species could survive but the map only denotes this with a dark green or red color (Figure 23). To find more information, the table needs to be analyzed. The solution to this would be another plot that would show the depths change as the user hovers over each station. Due to the lack of experience with R Shiny, the team was unable to create this plot. Another limitation to the app was the inability to incorporate the HSI created for the Dungeness crab into the application.

Introduction

This application is designed to interactively visualize cruise data collected by NOAA and cooperators and provide a platform to understand and review the suitability of marine species by inputting desired parameters to make a mock threshold. Source code and additional information for this application will be available via the GitHub repository.

Data

All data used by this application is available through National Oceanic and Atmospheric Association (NOAA). Data from NOAA West Coast Ocean Acidification 2021 (WCOA) cruises have been loaded. The cruise was designed to obtain a synoptic snapshot of critical carbon, physical, and biogeochemical parameters related to ocean acidification (OA) in the coastal realm. Parameters like ocean carbonate chemistry, acidity, salinity, temperature, oxygen, nutrients, carbon and nitrogen isotopes, and chlorophyll from 17 transect lines of stations stretching from British Columbia, Canada to San Diego, California were collected to analyze how the marine food web is being affected by warming, ocean acidification, and deoxygenation in this region. More information can be found on the NOAA cruise website.

Application Usage

The application has two main inputs: a map and a table.

The map shows all the stations available. The table shows all of those sites and their associated parameters. The map and table inputs are responsive to the sliders. This is best used when the user has a desired/hypothetical threshold for a given species. The map will display the stations where the criteria made match the parameters. This is better understood with the table: "High" means the station/area is suitable for the species. "Low/ Not suitable" means that the sliders' criteria were not able to fully match with any of the stations.

Try this sample threshold curated by the Habitat Suitability Index for the Dungeness Crab:
Depth: 60 - 120 meters
Temperature: 8.98 - 13.59 °C
pH: 7.47 - 7.95
Aragonite Saturation: 1.00 - 2.41
DO: 131 - 289 mg/L

Hint: To omit a parameter select the whole range.

Learn More: This app features only five parameters but there are many more factors that can determine a habitat's suitability. Learn more about the factors featured on this app:

- *Depth* is known to influence light intensity, water temperature, and nutrient ability. Some marine species migrate to deeper depths during the day and return to shallow depths during the night. This process is called vertical migration and is important to consider when looking at marine species' suitability.

- *Temperature* is another important parameter to consider when exploring different marine environments and understanding physiological tolerances. Organisms have a particular temperature range at which they can survive and reproduce. As we observe the warming of our oceans, we are likely to see a decrease in habitat suitability for many marine organisms.

- *Aragonite saturation* state is commonly used to track ocean acidification because it is a measure of carbonate ion concentration shell building minerals). With an aragonite saturation state less than 1, we might expect some shells and skeletons to dissolve. This would cause low suitablity for many calcifying organisms.

- Changes in ocean chemistry like *pH* can affect calcifying and non-calcifying organisms. Some marine organisms' shells and skeletons are made from calcium carbonate, which can dissolve due to changes in the oceanic carbon chemistry. These changes can also impact a species' ability to detect predators.

- All aquatic animals need *dissolved oxygen (DO)* to breathe and survive. Low levels of oxygen, known as hypoxia, or no oxygen levels, known as anoxia, can occur when there is an excess of organic materials. Low levels of oxygen limit the photosynthesis of phytoplankton and impact large-scale ecological activity.

This application was made possible through the R Shiny platform, using packages like leaflet and ggplot. For more information feel free to contact the team!

Figure 20. User Guide for the HSI Web-based App.

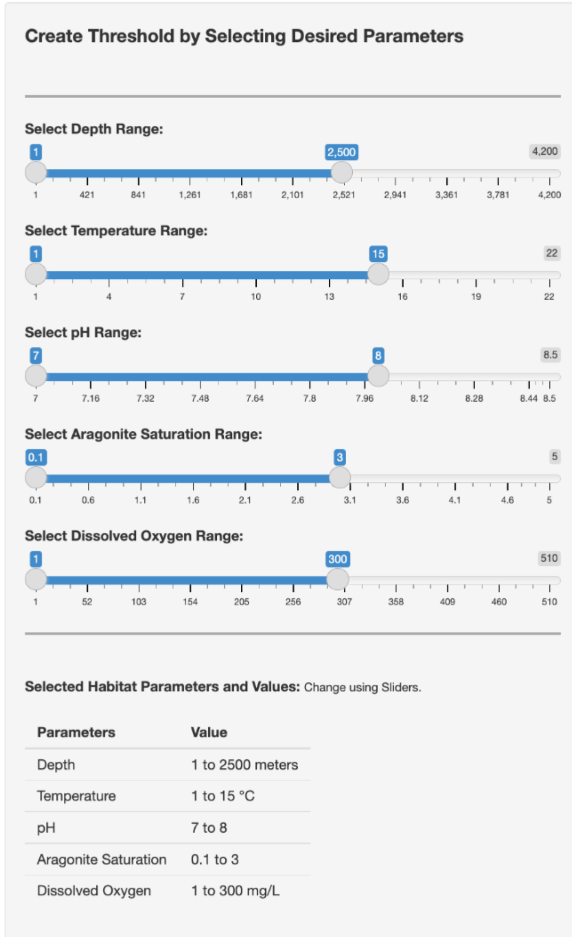

Figure 21. Control Sliders for Physical Parameters of the HSI Web-based App.

Table: The selected parameters are filtered. Explore the different places where you can find your species!

Show 10 entries

Search:

	Longitude	Latitude	Depth	Temp	pH	Omega	DO	Salinity	Sigma	DIC	TALK	Suitability
1	-130.85	51.46	1334.11	2.66	7.3	0.48	17.78	34.46	27.48	2386.65	2389.3	High
2	-130.85	51.46	1001.27	3.3	7.29	0.48	10.25	34.38	27.36	2376.05	2370.2	High
3	-130.85	51.46	752.01	3.83	7.27	0.48	11.55	34.25	27.2	2355.37	2342.7	High
4	-130.85	51.46	500.69	4.53	7.08	0.52	36.63	34.06	26.98	2317.6	2310	High
5	-130.85	51.46	251.26	5.95	7.42	0.76	119.94	33.87	26.67	2236.48	2270.7	High
6	-130.85	51.46	151.09	6.96	7.49	0.92	155.73	33.7	26.4	2192.59	2249.9	High
7	-130.85	51.46	125.05	7.26	7.51	0.94	166.78	33.54	26.23	2175.84	2235	Low/Not Suitable
8	-130.85	51.46	100.67	7.16	7.58	1.1	215.61	32.94	25.77	2123.23	2206.3	Low/Not Suitable
9	-130.85	51.46	81.22	7.32	7.64	1.21	255.71	32.53	25.43	2084	2181.3	Low/Not Suitable
10	-130.85	51.46	60.03	7.73	7.72	1.47	291.21	32.29	25.18	2040.37	2167.7	Low/Not Suitable

Showing 1 to 10 of 1,524 entries

Previous 1 2 3 4 5 … 153 Next

Figure 22. Table Output for the HSI Web-based App.

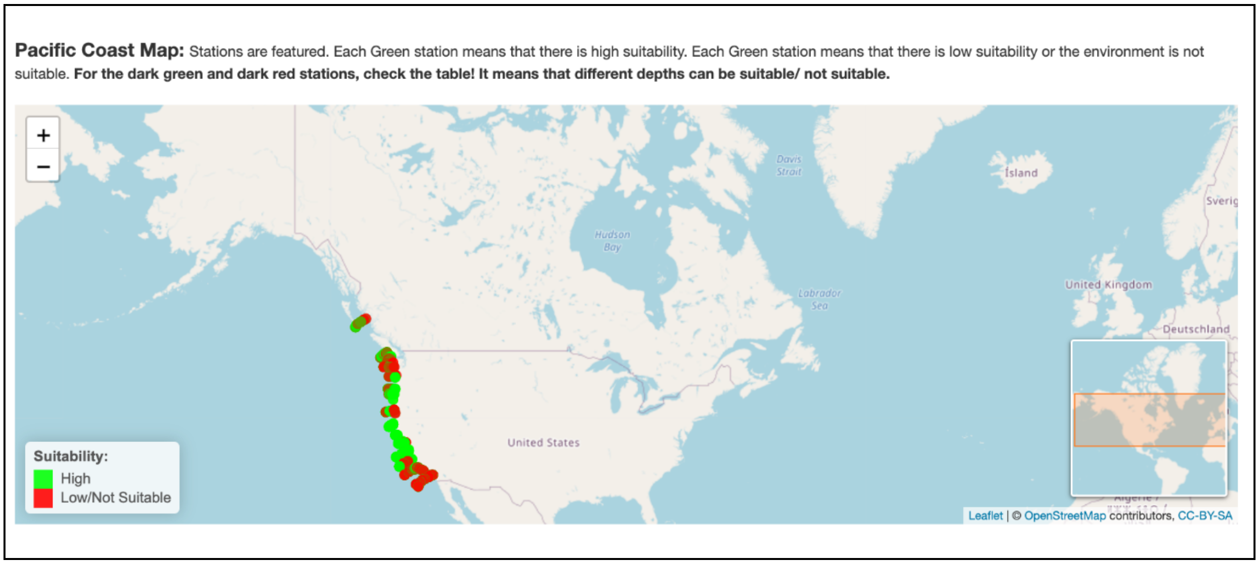

Figure 23. Map Output for the HSI Web-based App.

3C. Communication and Outreach

3C.1 Website

The website (found at https://isimonito.wixsite.com/dungeness) was designed by our team to communicate our research to a general audience and has received 116 visits as of the writing of this report. We did not have a certain amount of desired visits to this site in mind to count as a goal of "success." We take the approach that every visit to this site is another achievement for communicating science, the purpose of our research, and making it more accessible to the public.

3C.2 Outreach

The outreach event brought 25 new visitors to our project website. In addition, 14 of these visitors filled out the quiz associated with the outreach event, entering themselves into the running to win one of two 18 oz. Hydroflasks. A further 8 people interacted with our event without scanning our QR code to visit the website. Several of these interactions provided valuable insight into how our project could be best communicated to the public.

4. DISCUSSION

Plankton form the base of the marine food chain and have a disproportionate effect on the ecosystems they support. Thus, changes to the abundance or structure of primary producer communities may have serious repercussions for those ecosystems. In addition, phytoplankton sequester carbon, neutralizing its effects as a greenhouse gas, so alterations to primary production could jeopardize the ability of the oceans to absorb carbon dioxide and offset anthropogenic carbon emissions (Shurin et al., 2006). The effects of climate change on primary producers have been extensively studied, but the findings of these studies have been convoluted and have yielded few universal answers. The three main direct effects of climate change that have been assessed are seawater warming, seawater acidification, and an increase in DIC in the ocean, all of which are intrinsically connected. These factors have the potential to inhibit, promote, or have no effect on the growth of different primary producers, but these outcomes vary substantially across different ecosystems, species, and even subpopulations of the same species (Gao et al., 2012). It is thus important to understand how existing gradients in the CCS affect the planktonic community structure, and specifically what factors most affect each type of plankton. If we can understand how environmental parameters such as pH, temperature, nutrient concentration, and salinity affect the geographic distribution and abundance of plankton, then we can better predict how the changing conditions under climate change will affect the distribution and survival of planktonic groups.

Our results reveal some telling patterns in the planktonic community structure of the California Current System. At the Barkley Sound and Brookings transects, we saw nearshore community structure dominated by *Chaetoceros* and offshore community dominated by *Rhizosolenia*. This shift was accompanied by decreasing nutrient gradients moving away from the coast. We also saw the planktonic community of the Columbia River transect dominated almost entirely by *Rhizosolenia*. *Rhizosolenia* are nitrogen fixing diatoms that harbor symbiotic, nitrogen-fixing cyanophytes called Rhichelia and are found in brackish and marine waters (Abdala, 2020). They produce oxygen and biogenic particulate silicate and prefer warmer waters. These patterns seem to suggest that *Chaetoceros* dominates when nutrient concentrations are high, pushing out other plankton through direct or indirect competition. *Rhizosolenia* seems to thrive in areas with low nutrient concentration or low salinity (such as at the Columbia River outlet). This genus of diatoms may have much lower nutrient requirements than other groups of diatoms, allowing it to survive in ostensibly inhospitable environments. Our results also suggest, unsurprisingly, that abundance of plankton decreases as nutrients decrease from nearshore areas to the open ocean. This seems to be an important guiding principle in the dynamics of the CCS planktonic community.

In addition to nutrient concentration affecting the planktonic community makeup at each transect, there appear to be trends in the Shannon Diversity Index (SDI) value at each station and the abundance of varying taxonomic groups. The SDI shows that there is more diversity at the offshore stations in Transects 5 and 8, but that the nearshore station is more diverse in Transect 2. The offshore stations of Transects 5 and 8 show a few similarities that may be correlated to the higher diversity. This includes lower carbonate and phosphate concentrations, and higher oxygen and pH than their corresponding nearshore stations (Figure 27). The nearshore station in Transect 2 is more diverse, yet differs from the other stations that show high diversity by having higher carbonate and phosphate values than the offshore station. Each station that is more diverse has higher pH values than the other station in the transect. This may suggest that diversity is related to a higher pH, which is of particular interest due to the projected effect of declining ocean pH values due to climate change (Duarte et al., 2013).

In terms of North to South SDI values, Transect 8 is the most Southern transect and has the overall highest diversity, with the Transect 8 offshore station having the largest SDI value out of all the stations analyzed. Transect 8 has the highest oxygen, carbonate, temperature, and pH out of all the transects. These properties may be conducive to a large number of planktonic species. Transect 5 has the overall lowest diversity, which may be due to the influx of freshwater from the Columbia River limiting the number of species able to survive in this transect. However, SDI does not show a significant correlation to these parameters in our PCA, so further research is needed to identify a statistically significant relationship between environmental conditions and planktonic diversity.

These results may have implications for which species will dominate under climate change, especially regarding species whose abundance is correlated to ocean chemistry parameters. However, while we are able to make observations on how environmental gradients affect planktonic community composition, our results indicate a need for continued analysis on this topic. With only a few biological sampling stations at each transect, we are unable to produce a sufficient amount of statistical power in our analyses to make concrete conclusions about the entirety of the CCS. The short timeframe of this project restricted the complete exploration of the relationships identified by the PCA (Figure 14). We suggest that the relationships between all of the physical parameters and planktonic species are explored in a continuation of this research. Furthermore, there are potential limitations to our data, since there is a potential for human error when validating species on EcoTaxa. We suggest continuing to use EcoTaxa to validate images in order to create a dataset that includes the taxonomic compositions at every station throughout the CCS that has data available. This can then be used to explore these trends in greater detail, as well as determine if there are different planktonic community patterns related to other physical factors.

In addition to continuing this research with a greater number of stations, and thus larger statistical power, we see considerable potential for the use of this planktonic data. As expressed in Benedetti et al. (2019), studies exploring planktonic community structure and its relationship to environmental parameters can be of great use in understanding how Marine Protected Areas (MPAs) can achieve their conservation goals. Potential topics of interest for further research include investigating if planktonic communities differ in MPAs versus outside MPAs as well as using this planktonic data in conjunction with species abundance data from higher trophic levels, such as pelagic fish, mammals, and birds, to see if species abundances are correlated. We hope to see this research and any future projects used as a tool to ensure the conservation of marine biodiversity and resources in the CCS, and see our preliminary results as the first step toward this goal.

In addition to providing preliminary analysis in planktonic community structure in the CCS, our project assesses the suitability of *M. magister* off the North American West Coast. Not only do Dungeness crab have commercial importance, but planktonic stages of the species may help indicate the overall health of the aquatic ecosystem. Our research demonstrates that *M. magister* megalope are likely to be affected by anthropogenic climate change. Recent works provided by Oliver et al. (2018) predict the increase of frequency and duration of global marine heat waves in regard to global warming and ocean acidification. These trends can largely be explained by increases in mean ocean temperatures, suggesting that we can expect further marine heat waves under continuous warming conditions. With continuous ocean warming, we expect the distribution of *M. magister* to contract to a large degree as the ocean surface temperatures exceed the thermal habitat range for *M. magister*. The habitat ranges of other marine organisms are also predicted to shift due to ocean warming (Assan et al. 2020).

As marine species relocate to find suitable environmental conditions, tools such as the Habitat Suitability app will help researchers assess organisms' predicted habitat range. The generated map gives the users a better understanding of how limited and constrained ranges become as the parameters change. For a better comprehensive application, more abiotic data from NOAA would provide a larger geographic range that would allow for a wider scope of understanding. As the app improves, this can be used by scientists and students to support research about disappearing habitats and lowered suitability due to different global phenomena.

With respect to the future habitat range for *M. magister*, we considered the two specific climate scenarios under representative concentration pathways (RCP). Under RCP 8.5 scenario, we assume no greenhouse gas mitigation and the upper ocean temperature in CCS is projected to increase by 4 ℃ by 2100 under these conditions (Siedlecki et al., 2021). High anthropogenic CO_2 under RCP 8.5 will likely reduce the habitat range for *M. magister*. Under RCP 2.6 scenario, we assume strong mitigation effort as it requires the CO_2 emission to be zero by 2100. Unlike the high CO_2 emission scenario, RCP 2.6 suggests the greater preservation of habitat range for *M. magister*. However, Ω_{ar} is expected to decrease in both scenarios with the result of ocean acidification (Siedlecki et al., 2021). In the absence of strong mitigation efforts of CO_2 emissions, RCP 2.6 cannot provide the sufficient reduction to preserve the habitat range for *M. magister*. The reduction of Ω_{ar} can potentially reduce the habitat range of *M. magister* even at the cooler range which is under 10 ℃. The combination of change in temperature and Ω_{ar} suggest that we are expecting to see the reduction in habitat range of *M. magister* in CCS by 2100. As a result, we suggest the future research to quantify the habitat suitability reduction in *M. magister*.

Similar to Bednaršek et al. 2022, our findings suggest that a multi-stressor framework may be needed when determining the habitat limitations of marine organisms. As shown by Bednaršek et al. 2022, a single parameter framework may not sufficiently explain population-level responses. Past studies have often looked at the effects of a single driver (Christmas 2013; Miller et al. 2016); however, future analysis may benefit from a multi-parameter framework. A limitation to our interpretation is that we only accounted for linear relationships between two variables. We suggest that future studies evaluate nonlinearly relationships between the full range of hydrographic variables.

We also compared the habitat suitability between *L. helicina* and *M. magister* using pteropod thresholds found in Bednaršek et al. 2022. While the thermal habitat window for *L. helicina* was approximately 8–13°C, we found *M. magister* to survive in approximately 9–12°C. Given that Dungeness crab larvae have a more narrow thermal habitat range compared to pteropods, we expect their geographic distribution to be more constrained in the CCS. This assumption is supported by the coastal models produced by Deutsch et al. 2021 (Figure 18 and 19). In particular, latitudes below 40°N are less suitable for *M. magister* when compared to *L. helicina*. Peak abundances for *L. helicina* occurred at 10°C while peak abundances for *M. magister* occurred at 12°C. The thermal maximum for the *L. helicina* was 15°C while the thermal maximum of *M. magister* was 12°C, indicating that pteropods may be better suited for ocean warming. However, it is important to note that Bednaršek et al. 2022 analyzed pteropod data from all seasons while our HSI is based on data from June and July.

5. LITERATURE REVIEW

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7. Appendix

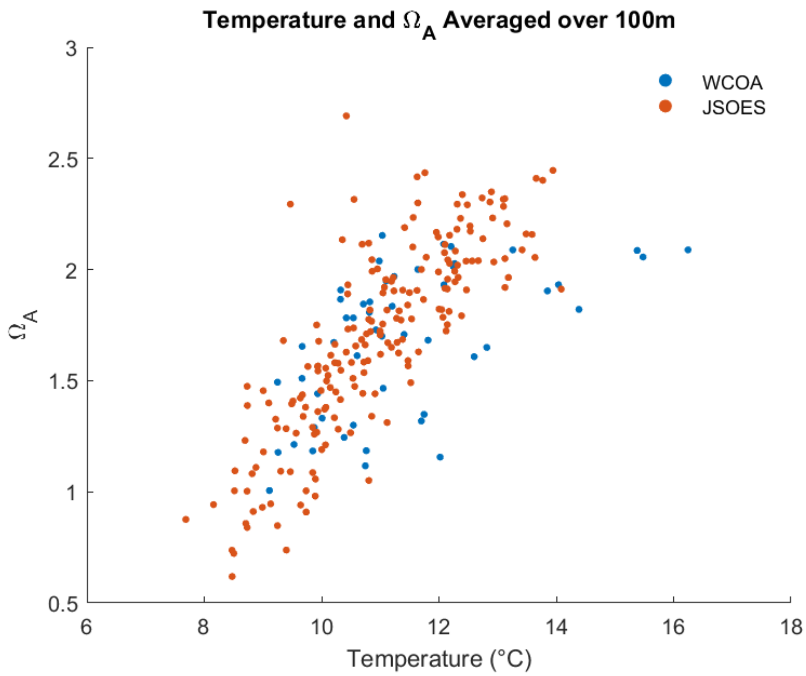

Figure 24: Averaged T and Ω_{ar} values for WCOA cruise (2016 and 2021) and JSOES time series (2015-2020)

Eqn.	α_0	P_1	α_1	P_2	α_2	SI
Temperature and Ω_{ar}	9.50	T	2.17	Ω_{ar}	-1.22	24.5%
pH and Temperature	-0.29	pH	1.30	T	-0.91	20.0%
pH and DO	93.1	pH	-12.8	DO	0.03	8.5%
DO and Temperature	8.9	DO	0.001	T	-0.86	19.8%

Table 2: Coefficients and SI values for WCOA HSIs.

Eqn.	α_0	p	P_1	α_1	p	P_2	α_2	p
Temperature and Ω_{ar}	9.50	0.010	T	2.17	0.096	Ω_{ar}	-1.22	0.004
pH and Temperature	-0.29	0.990	pH	1.30	0.690	T	-0.91	0.011
pH and DO	93.1	0.048	pH	-12.8	0.050	DO	0.03	0.122
DO and Temperature	8.9	0.011	DO	0.001	0.858	T	-0.86	0.008

Table 3: Coefficients and their corresponding p-values for *M. magister* WCOA HSIs.

Eqn.	α_0	p	P_1	α_1	p	P_2	α_2	p
DO and Temperature	-8.501	0.208	DO	0.019	0.1849	T	0.362	0.659

Table 4: Coefficients and their corresponding p-values for a *M. magister* JSOES HSIs.

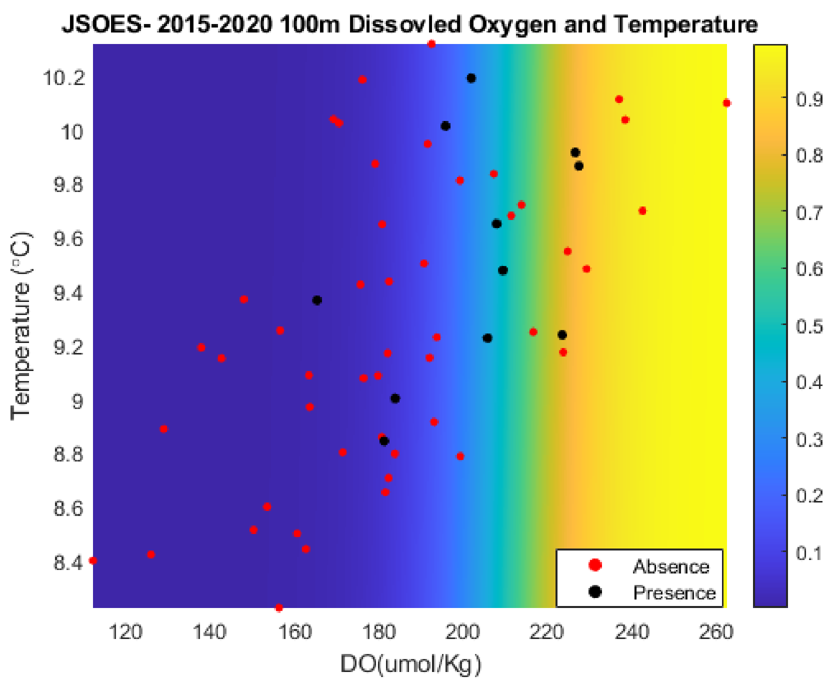

Figure 25. HSIs for *M. magister* using the combination of DO and Temperature. Predictions (background gradient) use JSOES (2015-2020) data while presence/absence observations (scatter plot) are using 2015, 2016, 2017, 2019 and 2020 data.

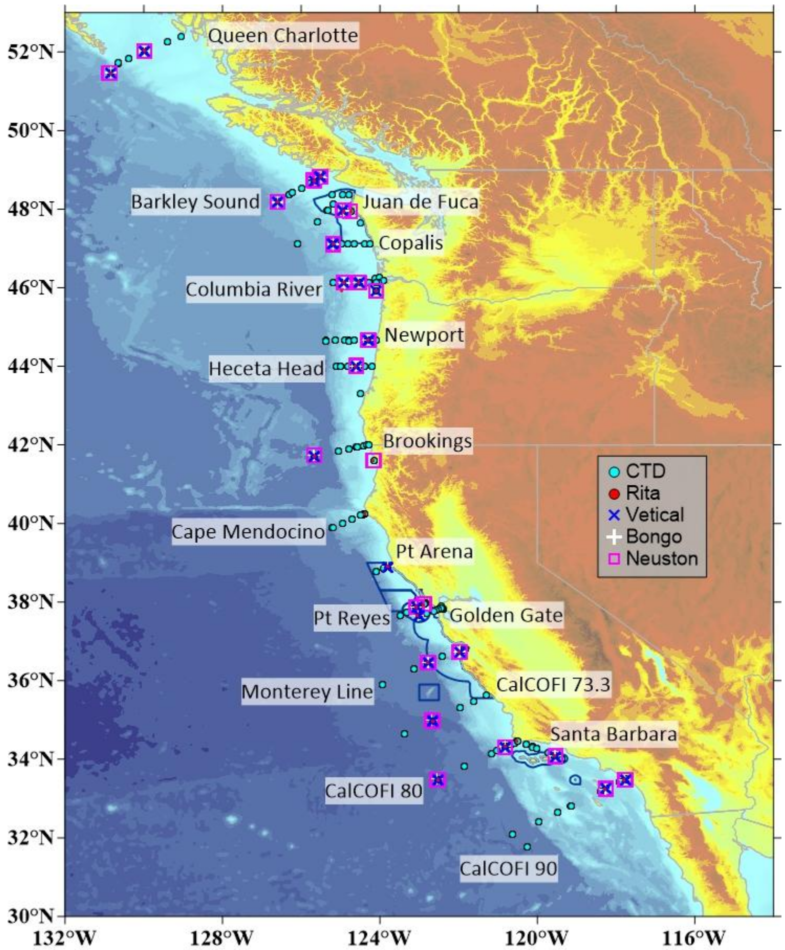

Figure 26. 2021 NOAA West Coast Ocean Acidification Cruise. Geographic boundaries 31.78°N to 52.40°N by 130.85°W to 117.75°W. Credit: NOAA website.

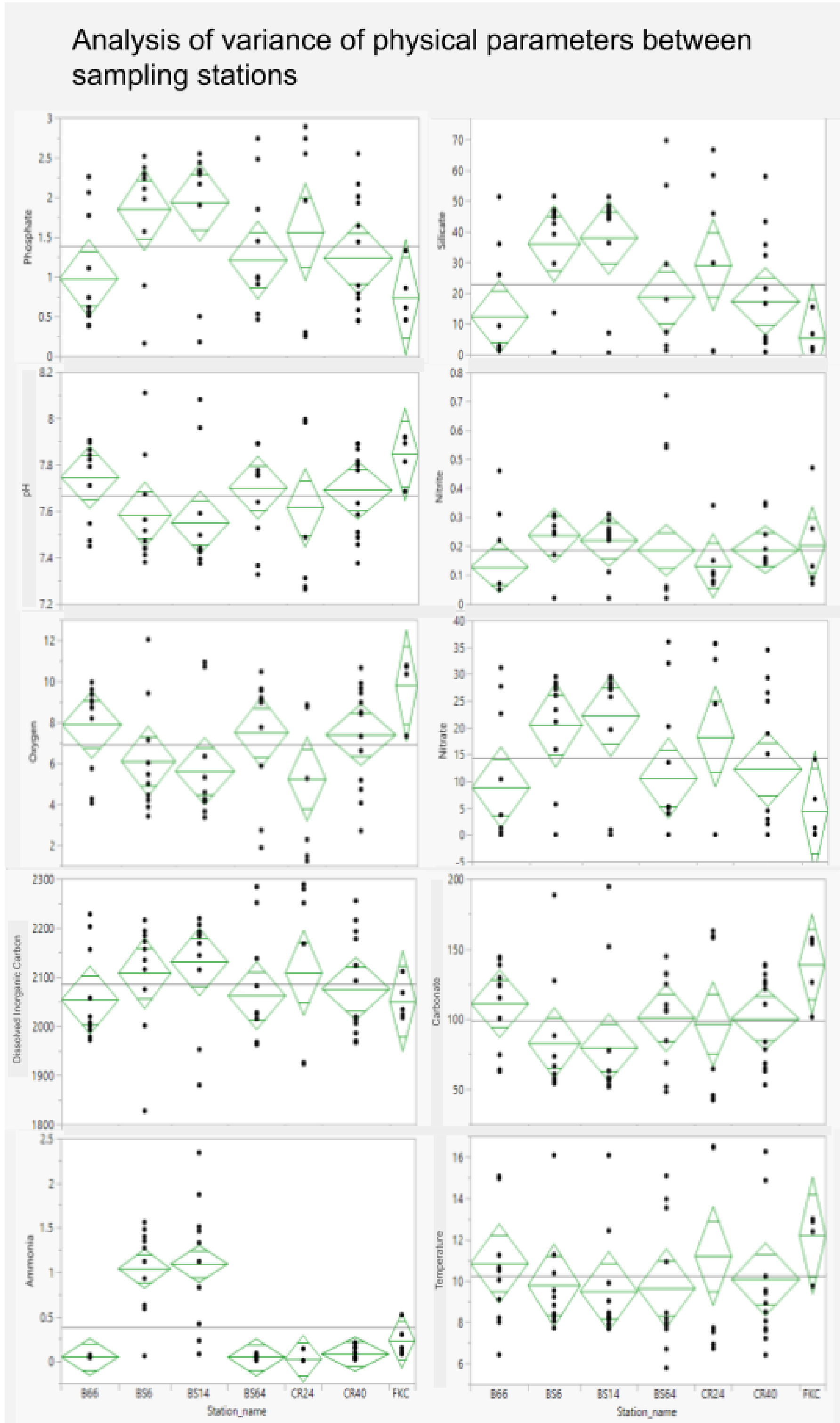

Figure 27. These plots display values measured in the upper 300m of the water column, separated by sampling station. Each plot includes a line to indicate the average value across all stations and distribution diamonds to highlight the spread within each sampling station.