



Phytoplankton Dynamics in a Cultivated Kelp farm off the coast of Namibia

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ABSTRACT

The rapid degradation of ocean habitats in the Anthropocene has significantly impacted marine ecosystems and fisheries, necessitating restoration efforts and sustainable practices such as the cultivation of *Macrocystis pyrifera* (giant kelp). This study examines the ecological impact of giant kelp farming on phytoplankton dynamics within the Benguela Current off the coast of Lüderitz, Namibia. Over two years (2022-2024), we monitored phytoplankton abundance, community composition across environmental gradients, and changes in alpha diversity indices across 5 adjacent sites at the surface, middle and bottom of the water column.

Initial data exploration revealed seasonal peaks in phytoplankton cell counts. 26 different genera were found to exhibit variability in total cell counts across different sites and depths. Notably, Shearwater Bay (site of kelp farm) showed the highest genera diversity with similar cell count across all genera. Conversely, Grosse Bucht (Control) exhibited the lowest number of genera and the lowest cell counts. Depth-specific trends indicated that surface levels (0 meters) consistently hosted all genera at the highest cell count, The cell count as well as number of genera gradually decreased deeper in the water column (15-, 30-meters depth). A large presence of genus *Chaetoceros* was found at Pilot and in the surface waters. The lowest presence was recorded at Shearwater Bay’s surface waters. Additionally, cell abundance seemed to be correlated with the availability of nutrients

Non-metric multidimensional scaling (NMDS) plots and PERMANOVA analyses indicated that community composition did not significantly vary by site or depth but was significantly influenced by CaCO₃ availability, particularly during winter and autumn.

Alpha diversity indices (Shannon, Simpson, and Inverse Simpson) demonstrated varying trends across sites and depths. Sites with cultivated kelp showed varied trends in Shannon diversity from 2022-2024, with significant increasing trends observed at Pilot, particularly at surface waters. Temporal trends in the Simpson and Inverse Simpson indices showed slight but non-significant changes.

Overall, the findings suggest that giant kelp farming influences phytoplankton community dynamics. These changes underscore the ecological role of kelp farming in modifying biodiversity and its potential downstream impacts on marine ecosystems. Further long-term studies are needed to elucidate the broader implications of kelp cultivation on marine

biodiversity and ecosystem functioning, particularly in light of ongoing anthropogenic pressures on the atmosphere and ecosystems alike.

INTRODUCTION

The Anthropocene has brought about the rapid degradation of marine habitats (Seaman, 2007), leaving our ocean ecosystems and fisheries in a poor state. Among these ocean ecosystems negatively impacted by climate change are kelp forests (Filbee-Dexter et al., 2016). *Macrocystis pyrifera*, known as giant kelp is commonly found in temperate waters and grows on rocky substrate (Schiel et al., 2015; Campos et al., 2020). Kelp forests, formed by giant kelp offer essential ecosystem services, creating critical habitats that support thousands of marine species (Schiel & Foster 2015). They are essential for sustaining and promoting the health of fisheries (Schiel & Foster 2015; Miller et al., 2018). Over recent years kelp forests have been subjected to an increase in degradation (Reed & Brzezinski 2009). This has resulted in many restoration and rewilding attempts/studies across the world (Campos et al., 2020; Westermeier et al., 2016; Sanderson et al., 2003; Hernandez-Carmona et al., 2000). Though *Macrocystis pyrifera* is usually found in areas with rocky substrates, they show a similar successional development over sandy substrates (Campos et al., 2020) demonstrating the resilience of this species.

In recent years there has been an increasing interest in the production of food, pharmaceutical products and cosmetics using farming of Kelp (Camus et al., 2019; Biancacci et al., 2022). Besides the economic value of cultivating kelp, some studies have suggested that kelp cultivation increases habitat provisioning, nutrient cycling and carbon sequestration (Buschmann et al., 2017; Gentry et al., 2020). This has resulted in afforestation attempts globally by farming kelp in areas where it did not naturally occur (Boyd et al., 2022).

Kelp Blue is among several companies to sustainably produce, cultivate and transform *Macrocystis pyrifera* (Giant Kelp) into eco-friendly products. Their mission also encompasses enhancing ecosystem biodiversity, promoting carbon sequestration, creating local employment opportunities, and educating communities on the vital importance of ocean health. Currently, Kelp Blue has 2 separate farms, off the coasts of Namibia and New Zealand. Their largest farm is located off the coast of Lüderitz in Namibia, within the Benguela Current. The Lüderitz Upwelling cell has naturally occurring kelp populations, the dominant species is *Laminaria Pallida* with some sporadic *Ecklonia Maxima*. Though *Macrocystis pyrifera* grows naturally in the Southern Benguela it has never been recorded at Lüderitz in Namibia.

The cold and nutrient-rich waters of the four major coastal upwelling systems in the world, including the Benguela Current produce environmental conditions favourable for kelp forests (Shannon et al., 2006; Hutchings et al., 2009, Gonzalez-Aragon et al., 2024). It extends along the coasts of South Africa, Namibia, and Angola. Here, longshore winds blowing equatorward bring cold, nutrient-rich water from the depths to the surface and push warm surface waters

toward the equator (Shannon, 2001; Bordbar et al., 2021). What sets the Benguela Current apart from other eastern boundary upwelling systems is its position, bordered by warm water at both its northern and southern boundaries (Hutchings et al., 2009; Lamont et al., 2019). This interplay of unique chemistry, hydrography, topography, and bathymetry combines to create one of the world's most productive ocean areas (Hutchings et al., 2009).

The dynamics of wind patterns play a pivotal role in the Benguela Current, driving upwelling and thus affecting regional biodiversity (Hutchings et al., 2009; Sakko et al., 1998). This upwelling system is divided into northern and southern Benguela by a strong upwelling cell near Lüderitz in Namibia (Bordbar et al., 2021; Hutchings et al., 2009). Among the various upwelling cells—Cape Point (34°S), Lüderitz (26°S), and Cape Frio (17°S)—Lüderitz shows the most pronounced upwelling trends (Hutchings et al., 2009). The Lüderitz upwelling cell is characterized by strong winds, turbulent mixing, and significant offshore advection. Its larger upwelling intensity, compared to other regions, is likely due to localized land-sea temperature differences that intensify wind stress (Bordbar et al., 2021). Additionally, wind patterns at Lüderitz exhibit notable decadal and seasonal variability, with the strongest winds typically occurring from October to February and the weakest from May to July (Iileka et al., 2019). Similar seasonal trends are observed in the southern Benguela (Lamont et al., 2019, 2014). For instance, a study in the Southern Benguela showed the most intense upwelling in October and the weakest in May, with the upper mixed layer significantly deeper in May than in October, indicating fewer upwelling events during this month (Lamont et al., 2014). Despite these strong annual and decadal fluctuations, there has been a linear increase in upwelling-favourable winds suggestive of coastal cooling (Lamont et al., 2019, 2018; Tim et al., 2015). This increasing trend in upwelling winds will influence upwelling dynamics and the overall ecosystem structure within the Benguela Current.

The nutrient-rich environment created by the Benguela Current's upwelling supports substantial primary production, sustaining diverse marine life (Shannon, 2001). Although Lüderitz provides an ideal environment for kelp growth, the combination of strong winds, a narrow continental shelf, and high turbulence prevents the formation of dense phytoplankton concentrations between 26°S and 29°S (Hutchings et al., 2009). Consequently, the largest phytoplankton biomass is found downstream of these winds, where the water is less turbulent (Shannon et al., 2006). Kelp farming has been found to reduce flow velocity, turbulence and sediment resuspension in highly turbulent eutrophic areas. It increases transparency in the water column, resulting in greater phytoplankton abundance and diversity (Jiang et al., 2020). Conversely, many species of red, brown and green macroalgae have been found to release allelochemicals which inhibit the proliferation of harmful algal bloom diatoms and dinoflagellates (Jiang et al., 2020; Jeong et al., 2000; Tang et al., 2015). Additionally, some specific genera (Taxonomy level – genus; plural) of diatoms are associated with kelp, largely as epiphytes (Mayombo et al., 2020, 2019; Liu et al., 2018; Jiang et al., 2020). Two species of kelp naturally occurring in the Southern Benguela and the Lüderitz upwelling

cell (*Laminaria Pallida* and *Ecklonia Maxima*) have been found to have associated epiphytic diatoms (Mayombo et al., 2020)

The role of phytoplankton in the Benguela region is particularly significant for fisheries and climate regulation (IPCC, 2014). Phytoplankton biomass exhibits annual variability influenced by small-scale physical processes (Keerthi et al., 2022) and minor biogeochemical changes in the region (Lamont et al., 2014). Fluctuations in upwelling systems can significantly impact phytoplankton populations and, subsequently, the structure and functioning of food webs (Lamont et al., 2014; Sakko et al., 1998). It was also found that in subtropical regions there is an inverse relationship between chlorophyll-a concentrations and sea surface temperature (SST) (Behrenfeld et al., 2006; Doney 2006). Marine phytoplankton are crucial to the global carbon cycle, contributing approximately half of the net global primary production (Sakko et al., 1988; Lamont et al., 2014; Gregg et al., 2003). They also contribute to global carbon sequestration (Polimene et al., 2017) through the Biological Carbon Pump (BCP). The BCP is facilitated by the capture of CO₂ by phytoplankton into Particulate Organic Carbon (POC) which is transferred into the deep sea by gravitational sinking (Polimene et al., 2017). Areas with sufficient nutrient levels promote the growth of larger phytoplankton species (e.g., diatoms) which sink more rapidly to the ocean bed than their smaller counterparts (Polimene et al., 2017, Jardillier et al., 2010). Different phytoplankton groups influence ecosystem and biogeochemical processes in varying ways, emphasising the need to understand community composition (Cermeno et al., 2006; Basu & Mackey, 2018). Given the sensitivity of phytoplankton and their crucial roles, it is essential to accurately estimate their biomass, primary production, and community composition. Such estimations are vital for understanding ocean carbon cycles and the ecological processes linked to fisheries in coastal ecosystems (Lamont et al., 2014, 2019; Cermeno et al., 2006; Basu & Mackey, 2018; IPCC, 2014). This is particularly relevant for the predicted instability of phytoplankton diversity under future climate scenarios (Henson et al. 2021)

The impact of kelp farming on local phytoplankton populations remains poorly understood (Jiang et al., 2020). Previous studies have differing results on the response of the phytoplankton population within cultivated kelp farms, some suggesting reduced phytoplankton abundance (Yang et al., 2015) and others increased phytoplankton abundance (Jiang et al., 2020). Since the establishment of the *Macrocystis pyrifera* farm off the coast of Lüderitz, there has yet to be an analysis of its impact on local phytoplankton populations and their temporal trends. This study aims to address the impact of giant kelp cultivation on the local phytoplankton dynamics.

RESEARCH QUESTIONS :

1. How has the introduction of the kelp farm in Lüderitz affected phytoplankton dynamics?

- What are the environmental factors affecting phytoplankton community composition?
- Has alpha diversity changed since the introduction of the kelp farm? Does this differ between sites with and without kelp cultivation?

Due to the high windspeeds and seasonal variations at Lüderitz, I hypothesize that phytoplankton dynamics in the region are largely affected by seasonal changes and wind patterns. Additionally, due to the introduction of kelp in Lüderitz, I would also expect the presence of some genera to increase and community populations to shift.

METHODS

Study Area

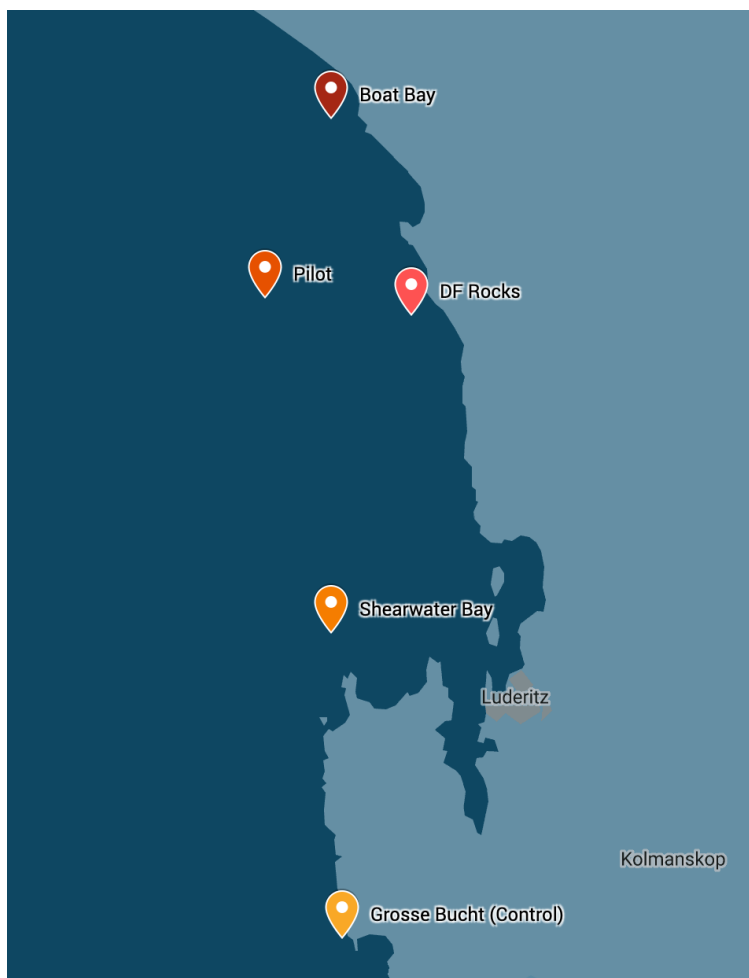


Figure 1: Study Area – Sites within the Lüderitz upwelling cell. Sites with cultivated kelp are Pilot and Shearwater Bay

The locations in this case study are off the coast of Lüderitz in Namibia (Figure 1). Five sites were selected for comparison and analysis: Shearwater Bay, Boat Bay, Dumfudgeon Rocks (DF

Rocks), Pilot and Grosse Bucht (Control). *Macrocystis pyrifera* or Giant Kelp is grown at two locations, Shearwater Bay and Pilot. Boat Bay and Dumfudgeon Rocks are close to the shore and Grosse Bucht is the control site. The farm at Shearwater Bay has 20 hectares of harvested kelp as of July 2024. This farm was introduced prior to the phytoplankton data collection (February, 2022). The kelp is grown by attaching the holdfast to a concrete block which is then placed at the seabed (around 10- meters depth). Pilot on the other hand had giant kelp introduced towards the later end of this study (August, 2023), the kelp here is grown at 15 meters depth on a netting structure of approximately 0.5 hectares. As of July 2024, harvesting is yet to take place at this site.

All sites were sampled at 0, 15 and 30 m depths, with the exception of Shearwater Bay and Grosse Bucht (Control), which are situated in shallow areas. Data collected at these two sites (phytoplankton and nutrients) was at a 0 m depth. Sampling done at different depths and sites can provide a clearer picture of the spatial variation of community composition among phytoplankton genera.

Phytoplankton Sampling

The sample collection, analysis of nutrients, and phytoplankton were carried out by Kelp Blue from July 2022 to July 2024 over several locations and depths. Phytoplankton were sampled using a 10 μ m mesh-sized net, white sampling bottles (chosen to avoid photolability), and a cooler box or storage box for maintaining sample integrity.

Prior to sampling all materials were labelled and the plankton net was rinsed in seawater which helped prevent contamination and maintain sample purity. It's crucial to ensure the bottom tap of the net is securely closed before lowering it into the water. The net was lowered to a depth between 0-5 meters (at the surface). The net is left submerged at a stationary position for a minimum of 3 minutes to capture an adequate phytoplankton sample. Upon retrieval, the sample bottle is positioned beneath the tap of the phytoplankton net, and the tap is opened to allow the net water to drain into the bottle. The collected sample is then stored in a closed box or cooler to protect it from direct sunlight, preserving its integrity until further analysis. This sampling is repeated at depths of 15 meters and 30 meters.

Preservation of Samples

The preservation of phytoplankton samples is crucial to maintain their cellular structure and integrity. This involves using Lugol's solution, a reliable fixative that preserves cellular morphology (Edler & Elbrächter, 2010; Williams et al., 2016). A 1% Lugol's solution (equivalent to 2.5 ml for each 250 ml sample) was used to preserve each sample immediately upon arrival. After preservation, samples were stored in a designated cupboard away from direct sunlight to prevent degradation. Properly preserved samples can be stored in these conditions for up to 12 months, ensuring longevity for subsequent analyses.

Analysis Using Utermöhl Method

Utermöhl's settling Method (Utermöhl, 1931; 1958) is a widely used method for quantitative phytoplankton analysis (Edler & Elbrächter, 2010; Vadrucci et al., 2018; McDermott & Raine, 2010; Bollmann et al., 2002). It involves the settling of phytoplankton using a sedimentation chamber before the microscopy analysis. For a more detailed description of Utermöhl's Method, I refer you to the book written by Edler & Elbrächter, 2010, pages 13-20.

Samples were prepared for analysis by applying petroleum jelly to the base of the sedimentation chambers. The chambers were then placed on the circular part of a microscope slide, ensuring stability and optimal viewing conditions. Each slide and sedimentation chamber setup is labelled according to the specific sample to maintain accurate identification and traceability. Before pouring samples into the sedimentation chamber, they are tilted and shaken for at least a minute to ensure even distribution and representation of phytoplankton cells.

Once the sedimentation chamber is filled to the brim, a round glass coverslip is carefully positioned over the chamber to avoid trapping air bubbles, which could affect microscopic examination. This setup is left undisturbed for 24 hours to allow phytoplankton cells to settle evenly, forming a convex shape at the top for optimal viewing under an inverted microscope.

After sedimentation, a clean square slide is positioned adjacent to the sedimentation sample. Using gentle pressure, the sedimentation chamber is carefully moved aside while ensuring the glass slide remains in place. The glass cover slip is then slid over the circular part of the microscopic slide, securing the sample for microscopic examination.

The prepared slide is placed on the stage of an inverted microscope, utilizing a magnification of 40x for detailed observation. The microscope is connected to a computer/laptop and viewed using the DinoCapture software which allows for ease in adjusting brightness and resolution to optimize image quality. Phytoplankton cells are identified manually and counted along three transects, starting from the middle left to the right side of the slide. The phytoplankton cells are identified at the genus level and the count data (per genus) is recorded on a dedicated sheet and entered into Fastfield or another appropriate database for analysis and reporting purposes.

Data Analysis

All data analysis was done using R Studio version 2023.12.1+402. To analyse the data accurately, it was organised and aggregated the samples. Genera (Taxonomy level – genus; plural) with observations < 10 cells total over the two years were removed, this was done to minimize "rare" genera. It is also important to note that the data had a large number of zeros, due to few sporadic presence and large periods of absence of "rare" genera; even after dropping genera with a total cell count below 10. This poses a problem when studying

diversity indices as many models are sensitive to 0 values, especially in this study where a value of 0 is not missing data. To address this, the data were transformed using the $\log(\text{cell count} + 1)$ for alpha diversity and the square root ($\text{cell count} + 1$) for beta diversity, which have been used in other ecological studies (Cao & Hawkins, 2005; Wright et al., 1995)

The phytoplankton data was also aggregated by the sum of each genus by a unique combination of site, depth, month and year. Here month was used as a grouping factor to remove potential outliers. As a start, changes in abundance and nutrients over time were visualized. A plot was created to understand changes in dominant genera over time as well.

Alpha & Beta diversity

For diversity studies in R Studio, the 'vegan' package was used. To study Alpha diversity we used 3 indices, the Shannon Diversity Index, the Simpson Diversity Index and the Inverse Simpson Index. These indices are widely used in the field of genetics and ecology (Uusitalo et al., 2013; Gorelick 2006; Kim et al., 2017). Measures of biological diversity take into consideration both the richness and evenness of species distribution. Richness focuses on the number of genera in a given sample, while evenness compares how similar the population sizes of different species are (Kim et al., 2017). Shannon diversity Index can be explained as the uncertainty of predicting the species of a randomly chosen individual in a group (Morris et al., 2014). In groups with larger species diversity which are evenly spread out in number, there arises a higher uncertainty of predicting the species of a randomly chosen individual. Conversely, uncertainty decreases in a group with fewer species which are less evenly distributed (Morris et al., 2014). Simpson's index measures the probability that two randomly chosen individuals are from the same species (Morris et al., 2014). A higher value of the Simpson's index indicates a lower diversity of species. For a more intuitive understanding of the Simpson's Index, the Inverse Simpson's Index is used ($1/D$) this can be interpreted as the effective number of dominant species, where a higher value can be interpreted as higher diversity (Morris et al., 2014). Though both Shannon's diversity index and Simpson's index have been criticized for biases, when used together they can provide a good understanding of population richness and evenness (Kim et al., 2017).

Additionally, a linear model on the Alpha diversity indices over time was used. This is used to aid the understanding of the changes in diversity over different sites and depths and if these changes are statistically significant. A Shapiro-Wilk test conducted on the residuals ($p > 0.05$) deemed the linear model a good fit for all three of the Alpha diversity indices trends.

To study the Beta diversity of the samples the Bray-Curtis Index was used, it is widely used to plot and understand ecological distances (Ricotta & Podani, 2017; Thakur et al., 2019). That is, the index examines the similarity/dissimilarity between adjacent locations with respect to

species composition. The Bray-Curtis Index was selected because the phytoplankton data is count data.

Visualization of species composition was performed using non-metric Multidimensional scaling (NMDS) plots with environmental vectors. NMDS is frequently used to characterise spatiotemporal dissimilarity (Cao & Hawkins, 2005; Xu et al., 2018). Similar to the aggregated phytoplankton data, environmental variables were also aggregated by the mean value of each unique site, depth, month and year combination. This was done to ensure a proper match between phytoplankton and nutrient data during the NMDS plotting. The environmental vectors used were the mean Nitrogen: Phosphorus(N:P) ratio, mean Phosphate, and mean CaCO₃. The N:P ratio was calculated using the formula $(\text{Nitrate} + \text{Nitrite}) / \text{Phosphorus}$. Furthermore, the integration of environmental gradients in the NMDS helps us understand the factors that affect community populations. To understand if the difference in community composition is affected by site, depth, and other various environmental factors a PERMANOVA on the Bray-Curtis matrix using the “RVAideMemoire” package in R Studio was used. PERMANOVA is generally used to accompany ordination models like the Bray-Curtis Index (Anderson, 2014; Kelly et al., 2015). The assumptions of a PERMANOVA are not explicit in regards to the distribution of original variables or dissimilarities. The main assumption is that the samples labels/names can be exchanged without affecting the overall structure of the data (Anderson, 2014). It looks at how the distances/dissimilarities can be explained by grouping or other factors, making it an ideal test to understand the effects of environmental variables on community composition.

RESULTS

General trends:

During initial data exploration, seasonal peaks in phytoplankton cell counts were observed (Appendix Figure 6). Twenty-six different genera of phytoplankton were observed, each of which showed peaks in cell count at different times between the years 2022-2024. The peaks in cell counts occurred in both 2023 and 2024. These peaks in abundance occurred around the same time as peaks in N:P availability (Appendix Figure 7). Variability in total cell counts per genera was noted across different sites and depths.

The summed cell counts of phytoplankton genera were observed over different sites and depths (Appendix Figure 8). Grosse Bucht (Control) exhibited the lowest diversity of genera. In contrast, Shearwater Bay showed the highest diversity, with cell counts ranging from 500 to 1,000 cells per genera. Pilot demonstrated the highest cell counts per sample, often exceeding 1,000 cells per genera over 2022-2024, with lower overall genera diversity. Boat Bay and Dumfudgeon Rocks exhibited similar genera composition, with Boat Bay showing lower summed cell counts.

Furthermore, genera presence varied with depth in the water column (Appendix Figure 9). At surface level (0 meters), all genera were consistently present and showed the highest cell counts. As expected, the cell counts as well as genera present decreased deeper in the water column (15- and 30-meters depth). With the number of genera and cell count the lowest at 30-meters depth.

Environmental Variables and Community Composition:

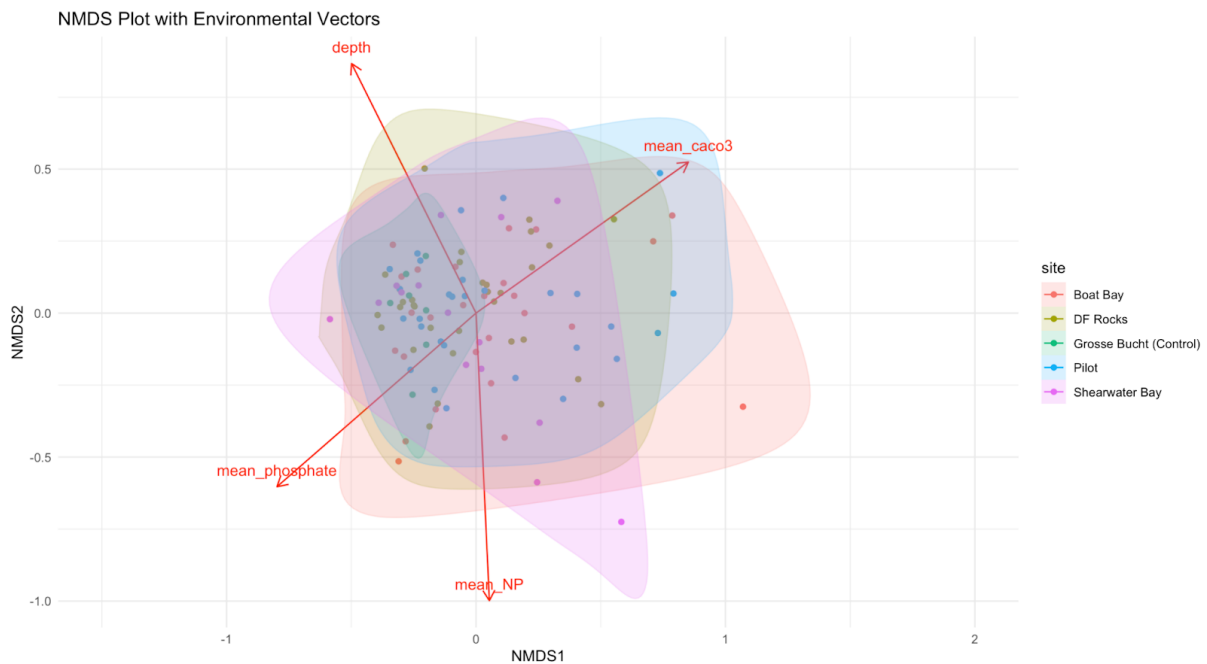


Figure 2: NMDS clustered by site. Environmental vectors are depth(m), mean calcium carbonate CaCO_3 , mean phosphate and the mean Nitrogen: Phosphorus ratio. The longer line of CaCO_3 indicates a stronger impact on community composition. The direction of arrows point towards higher values of the environmental variable – Points close together represent similar genera composition

The ecological distances between sites were visualized using an NMDS plot to explore species diversity across various environmental gradients. The stress level of the NMDS was below 2. Initially, points were grouped by site (Figure 2) but little variation was found in community composition. A PERMANOVA confirmed that the community composition does not vary significantly between sites, instead community composition varied significantly because of CaCO_3 availability. Here the community composition of points in the NMDS are spread out further around the CaCO_3 environmental vector, indicating that the community composition varies more depending on the CaCO_3 availability. When grouping points by season instead of site (Figure 3), more distinct patterns in community composition emerged. In winter, community composition was predominantly influenced by CaCO_3 and phosphate availability. Conversely, during autumn, both CaCO_3 availability and the mean N:P ratio played significant roles. Summer exhibited an equal influence from all four environmental variables. Notably, spring in Namibia, lasting only one month (September), showed indications of being influenced by depth and phosphate; however, the limited data points precluded definitive conclusions.

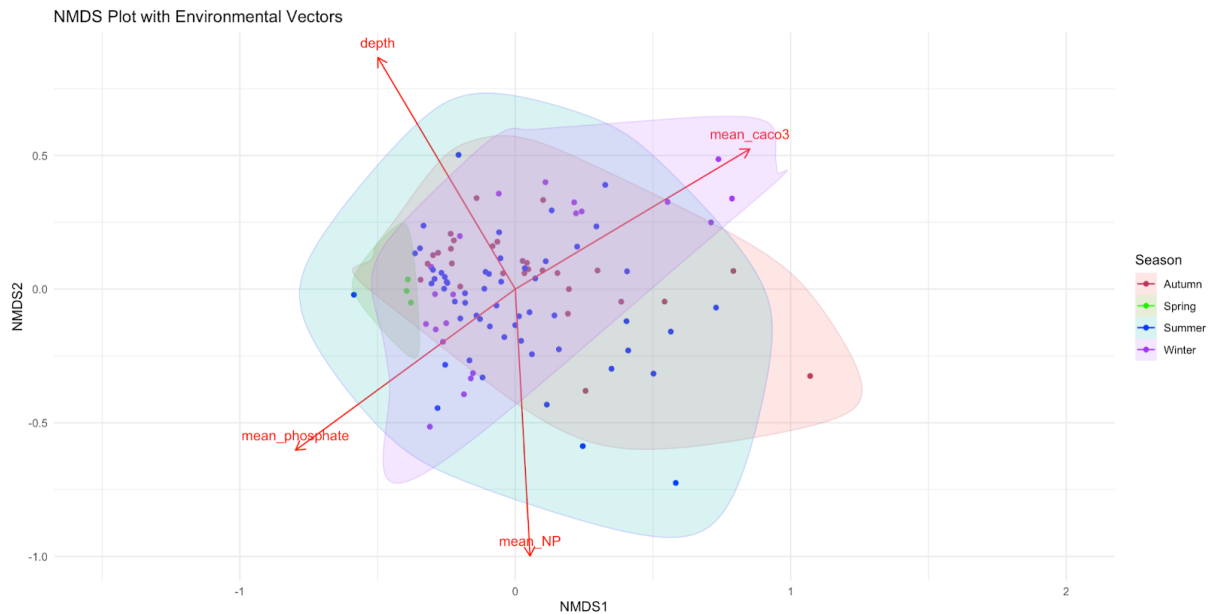


Figure 3: NMDS clustered by season Environmental vectors are depth(m), mean calcium carbonateCaCO3, mean phosphate and the mean Nitrogen: Phosphorus ratio. The longer line of CaCO3 indicates a stronger impact on community composition. The direction of arrows point towards higher values of the environmental variable – Points close together represent similar genera composition.

A PERMANOVA analysis of the Bray-Curtis dissimilarity matrix indicated that site and depth did not significantly affect community composition. In contrast, seasons had a significant impact ($p < 0.05$). A pairwise comparison showed community composition in spring to differ significantly from all other seasons. The fewer data points in spring may contribute to this observed distinction. Furthermore, the PERMANOVA showed both mean phosphate and mean CaCO3 were found to significantly influence community composition ($p < 0.05$). Notably, CaCO3 exerted the most pronounced effect ($p = 0.001$), explaining 6.3% ($R^2 = 0.0634$) of the variation in community composition. Phosphate accounted for 1.2% of the variation ($R^2 = 0.012$).

Alpha Diversity:

Alpha diversity was examined using different indices. Shannon index (Appendix Figure 10), Simpson Index (Appendix Figure 11) and Inverse Simpson index (Appendix Figure 12). All three indices show no consistent changes over different sites and depths. A linear model was used to assess the changes in Alpha diversity over time by different sites and depths.



Figure 4: Linear Model of Shannon Index over Time by different sites and depths. x- axis represents time and y axis is Shannon diversity.

First the temporal trends in Shannon Diversity was analysed (Figure 4) . The three sites without harvested kelp growth showed varied temporal trends from 2022-2024. At Boat Bay, the Shannon index displayed varied patterns at different depths. A slight increasing trend was observed at the surface and bottom waters (0- and 30- m). At 15 m depth, there was a marginal decreasing trend. At DF Rocks, the Shannon index at 0 m depth showed a decreasing trend. At 15 m depth, the trend was nearly flat. At 30 m depth, there was a minimal positive trend. In the control site, Grosse Bucht (Control), the surface (0 m) did not show changes in the Shannon index. Though the trends varied differently across these sites and depths none of them were found to be statistically significant ($p > 0.05$). Additionally Shearwater bay showed no notable trends in the Shannon index . None of these trends were found to be statistically significant ($p > 0.05$).

Conversely, at Pilot all three depths showed an increase in Shannon diversity index over time. A statistically significant increasing trend in Shannon index was observed at the surface (0 m) ($p = 0.01$). The trends at both 15- and 30- meter depths, the trend was not significant ($p = 0.224$) which may be attributed to a slightly lower sample size.

A linear model was used to analyse Simpson (Appendix Figure 13) and Inverse Simpson indices (Appendix Figure 14). Similar to the Shannon index, slight changes in temporal trends were found with no consistent changes over sites and depths.

Sites without cultivated kelp showed a slight increase in Inverse Simpson Index over time with the exception of Boat Bay at 0 meters depth with showed a slight negative trend. Similarly, at Shearwater Bay the Simpson index has increased slightly from 2022-2024. Pilot, on the other hand showed decrease in Inverse Simpsons Index over all depths, indicating more

pronounced dominance of a single genus. None of these changes were found to be statistically significant ($p > 0.05$). The Simpson index had opposite trends to the Inverse Simpson Index, none were found to be statistically significant ($p > 0.05$).

To understand the change in both the Simpsons and Inverse Simpsons Index, at sites with cultivated kelp, a deeper look into the genus dominance over time was conducted (Figure 5). This was done by plotting dominance (%) of genera over time. There was a shift in community composition at Shearwater Bay. Notably, initial samples showed a dominance of *Synedropsis* and *Asteromphalus* with minimal presence of *Thalassiosira* or *Skeletonema*. The presence of *Thalassiosira* and *Skeletonema* was found to increase over time. Interestingly, both genera were found in other samples taken at different sites at the same time. Other genera with a notable presence include *Thalassionema*, *Asteromphalus*, *Chaetoceros* and *Pseudo-nitzschia*.

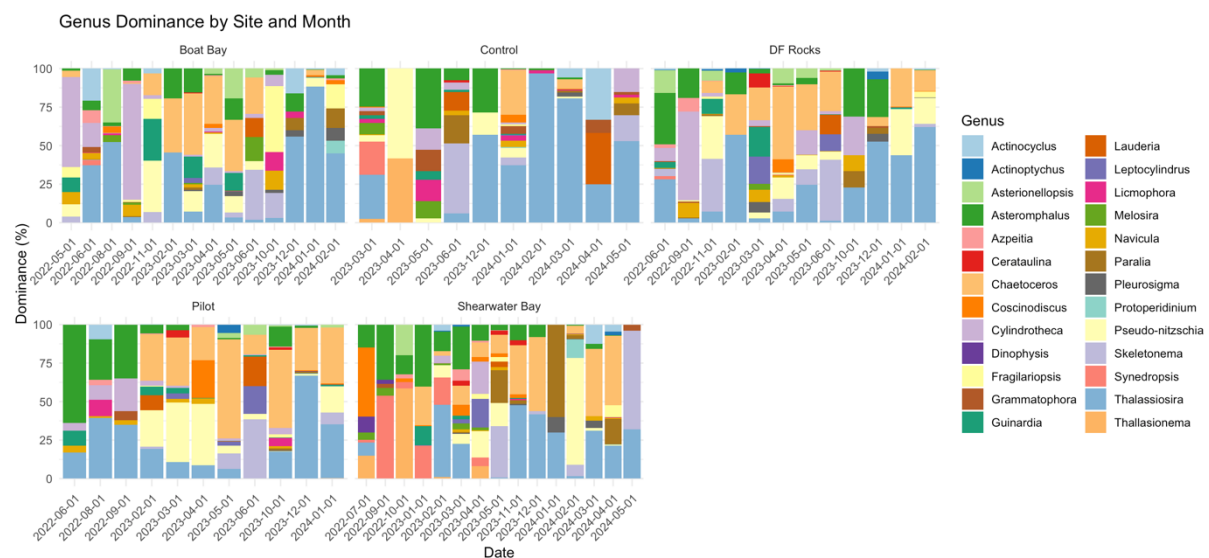


Figure 5: Dominance (%) of different genera over different sites. The y axis represents the dominance in % and the x-axis represents time

While temporal trends in alpha diversity indices varied markedly between sites and depths, significant changes were primarily observed in sites with harvested kelp, particularly at Pilot, indicating potential ecological impacts of kelp cultivating practices on phytoplankton community dynamics.

Overall, the Shannon diversity index across the sites and depths showed varied trends over the years 2022 - 2024. Changes at Boat Bay, DF Rocks, Grosse Bucht (Control) and Shearwater Bay did not show statistically significant changes across varying depths. Conversely Pilot showed changes which are statistically significant at depths of 0 meters while changes at 15 and 30 meters are not statistically significant. Areas with cultivated kelp showed different responses in Shannon Diversity, at Pilot there was an increase in Shannon diversity over all depths even if not statistically significant. Both the Simpson and Inverse Simpson index showed some changes through time though these changes were not significant.

Limitations

The phytoplankton collection and analysis have no values in December 2022 and January 2023 and again from June to September 2023. These missing data points may have an effect during data analysis. This also limits the data analysis as we cannot conduct accurate comparisons from the same season in different years. Furthermore, the Shannon diversity index has been criticized as biased; the error rate was lower when genetic diversity (heterozygosity) was higher especially in small samples with many genetic variations (Konopiński, 2020). In simple words Shannon diversity index is biased to species richness while the Simpson diversity index is biased to the evenness of species distribution (Kim et al., 2017). The study took place over two years, which is a relatively short period of time, this precludes definitive conclusions about changes in diversity.

DISCUSSION

The cultivation of *Macrocystis pyrifera* (giant kelp) in the Benguela Current off Lüderitz presents a unique opportunity to examine the ecological impacts on phytoplankton dynamics and community structure. This study aimed to investigate these impacts through the analysis of phytoplankton genera diversity, community composition across environmental gradients, and changes in alpha diversity indices over time. The data collected over two years 2022-2024 gives us a glimpse at the early changes in phytoplankton dynamics within and around a cultivated kelp farm.

Environmental Factors Shaping Community Composition

Phytoplankton dynamics within the Lüderitz upwelling cell are largely affected by seasonal variation which supports several studies in the area (Shannon, 2001; Hutchings et al., 2009; Bordbar et al., 2021). Peak phytoplankton cell counts are directly correlated to the availability of nutrients, thus, a higher phytoplankton abundance is found during periods of upwelling which increases the N:P ratio (Tilman et al., 1982; Chen et al., 2004) . While site and depth did not significantly affect community composition, we found that community composition is significantly affected by CaCO₃ availability. Notably, in winter months community composition is more affected by CaCO₃ and phosphate which could potentially be limiting nutrients during winters when the water is cold. When the water is warm during summers all environmental factors shape community composition.

Impact of Kelp Farming on Phytoplankton Dynamics

Shannon diversity within cultivated kelp at Pilot has increased at all depths, while the surrounding areas have had inconsistent changes in diversity. Though the overall diversity of phytoplankton species increased Pilot; a dominant genus became more pronounced as seen

from the Inverse Simpson index. This inverse relationship between richness and evenness was also found in a similar study by Jiang et al., 2020. Furthermore, there are several studies that show that kelp farming increases phytoplankton biodiversity (Hou et al., 2011; Yang et al., 2015). The increased presence of dominant species could be due to epiphytic phytoplankton which grows on the blades/ thallus of kelp (Foster, 1975; Myambo et al., 2019; Costa et al., 2016) or phytoplankton using its niche (Otero et al., 2020). Since Pilot had *Macrocystis pyrifera* introduced towards the end of this study there may not be a direct correlation between kelp and the changing phytoplankton community structure. This is especially relevant as the farm is only 0.5 hectares and was introduced in August 2023. Furthermore, the decreased Inverse Simpson is not likely a response to kelp cultivation.

Shearwater Bay, which had *Macrocystis pyrifera* introduced before the beginning of this study interestingly showed negligible changes in Shannon diversity while the Inverse Simpson Index has increased over the two years 2022-2024. These findings are the opposite of what was observed at Pilot. A minimal change in richness but an increasing trend in the evenness of species, meaning dominant genera became less pronounced. This directly contradicts the findings of Jiang et al., 2020 who found kelp farming significantly increases diversity but increases dominance. It is also important to note that Jiang's study looked at data collected over seven years, while this study looked at data collected only over two years. Previous studies demonstrated that kelp reduces flow velocities as well as turbulence (Hurd, 2000; Zhang et al., 2016). The decreased turbulence results in more light penetration, supporting phytoplankton diversity (Jiang et al., 2020). This could potentially explain the increased evenness of genera at Shearwater Bay. Additionally, there was a shift in community composition with initial samples showing dominance of *Synedropsis* and *Asteromphalus* while samples taken at the end of the study showed the dominance of *Thalassiosira* and *Skeletonema*. The presence of long-chained diatoms, namely *Chaetoceros*, *Thalassiosira* and *Skeletonema* have been found to be associated with kelp cultivation (Jiang et al., 2020) suggesting an impact of kelp cultivation on phytoplankton community composition in the Lüderitz area. Since water in this region moves equatorward the farm at Shearwater Bay may have downstream impacts at other sites, though there is no evidence to support this.

The Lüderitz upwelling cell is characterized by highly turbulent waters which prohibits the growth of phytoplankton. This upwelling cell also has a considerable amount of offshore advection which moves water and phytoplankton equatorward. The increase in phytoplankton diversity and/or evenness despite these environmental factors is particularly interesting.

Phytoplankton Dynamics on Ecosystem structure and functioning.

A larger diversity in phytoplankton results in better ecosystem functioning (Otero et al., 2020). This is because different species of phytoplankton fit different niches and use limiting

resources, like light or nutrients more efficiently (Otero et al., 2020; Cermeno et al., 2006). A study done by Otero et al., 2020 suggested that this is important during periods of upwelling where the larger availability of nutrients facilitates the coexistence of a larger number of species. These ecological niches are also likely what causes the pronounced dominance of certain species at Pilot. Additionally, greater diversity in phytoplankton can lead to a more stable and productive base (Vallina et al., 2017; Vallina et al., 2014), supporting a wider range of zooplankton (Otero et al., 2020) and, potentially, higher trophic levels such as fish, marine mammals, and birds (Borics et al., 2021).

Given the short time period of this study and lack of data points, it is difficult to come to a definitive conclusion regarding the changes in phytoplankton biodiversity, especially at Pilot. There needs to be further studies over time that integrate other environmental factors, such as light penetration, turbulence, temperature and flow velocities. Since there are changes in phytoplankton diversity, it would be advisable to investigate the direct impacts of these changes on the macro biodiversity. Similar research in the field should be a priority in the coming years as kelp farming becomes more popular. Studies within kelp farms could help advise ecosystem restoration at a time when wild kelp forests are greatly exploited and degraded by anthropogenic changes to the environment and local ecosystems.

CONCLUSION

The cultivation of *Macrocystis pyrifera* in the Benguela Current off the coast of Lüderitz, Namibia, presents a promising approach to mitigate the degradation of ocean habitats and enhance marine biodiversity. This study, conducted over two years, provides valuable insights into the impact of giant kelp farming on local phytoplankton dynamics and community structure.

Seasonal variations in phytoplankton cell counts were observed, with distinct peaks correlating with environmental factors such as Nitrogen: Phosphorus and phosphate availability. While site and depth did not significantly influence community composition, CaCO₃ and Phosphorus did have a significant influence. The influence of CaCO₃ and Phosphate on community composition was seasonal. The CaCO₃ and phosphate determined community composition, especially in winter and autumn.

Alpha diversity indices revealed an increase in phytoplankton diversity at Pilot, suggesting that kelp cultivation may enhance local biodiversity. However, the dominance of certain species at this site indicates complex ecological interactions that warrant further investigation. The increased diversity and altered community composition highlight the potential ecological benefits of kelp farming, including improved ecosystem functioning and stability. The greater evenness of genera and shift in community composition at Shearwater Bay are suggestive of an ecological shift.

These findings underscore the importance of long-term monitoring and comprehensive studies to fully understand the ecological impacts of kelp farming. As kelp cultivation gains popularity, it is essential to consider its role in ecosystem restoration and its potential to support marine biodiversity in the face of ongoing environmental challenges. Future research should focus on integrating additional environmental factors and exploring the broader implications of kelp farming on higher trophic levels and overall marine ecosystem health.

In conclusion, while this study provides preliminary evidence of the positive impacts of giant kelp farming on phytoplankton diversity and community structure, further research is necessary to confirm these findings and guide sustainable kelp farming practices. By enhancing the understanding of these dynamics, we can better inform conservation and restoration efforts aimed at preserving and rehabilitating vital marine ecosystems.

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APPENDIX :

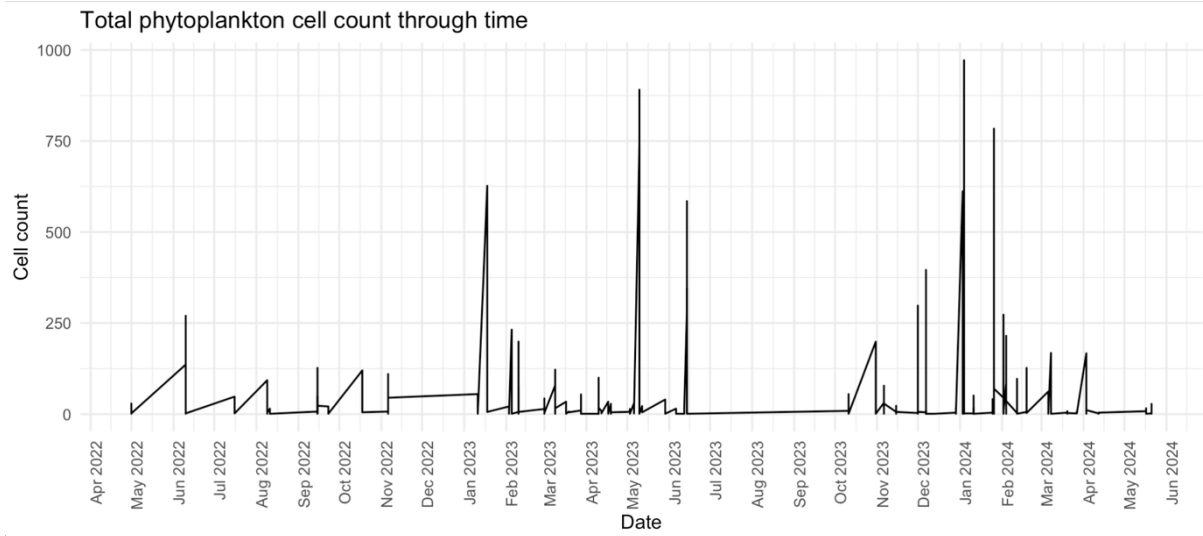


Figure 6: Phytoplankton cell abundance from 2022-2024

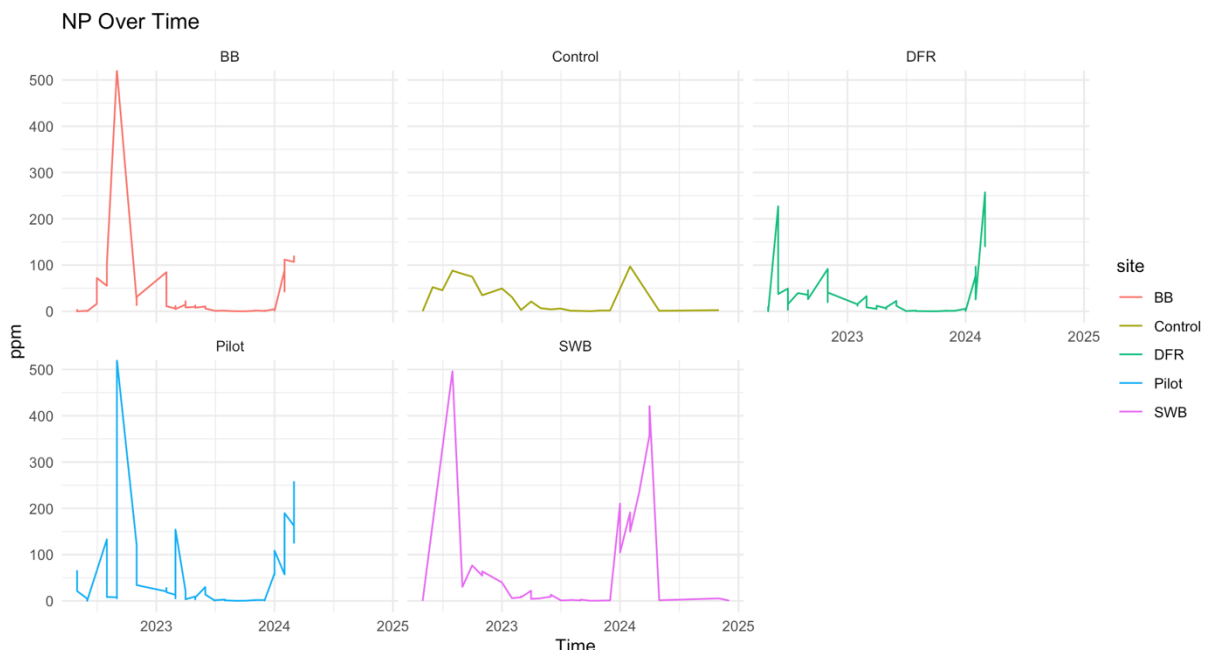


Figure 7: N:P ratio from 2022-2024 over different sites.

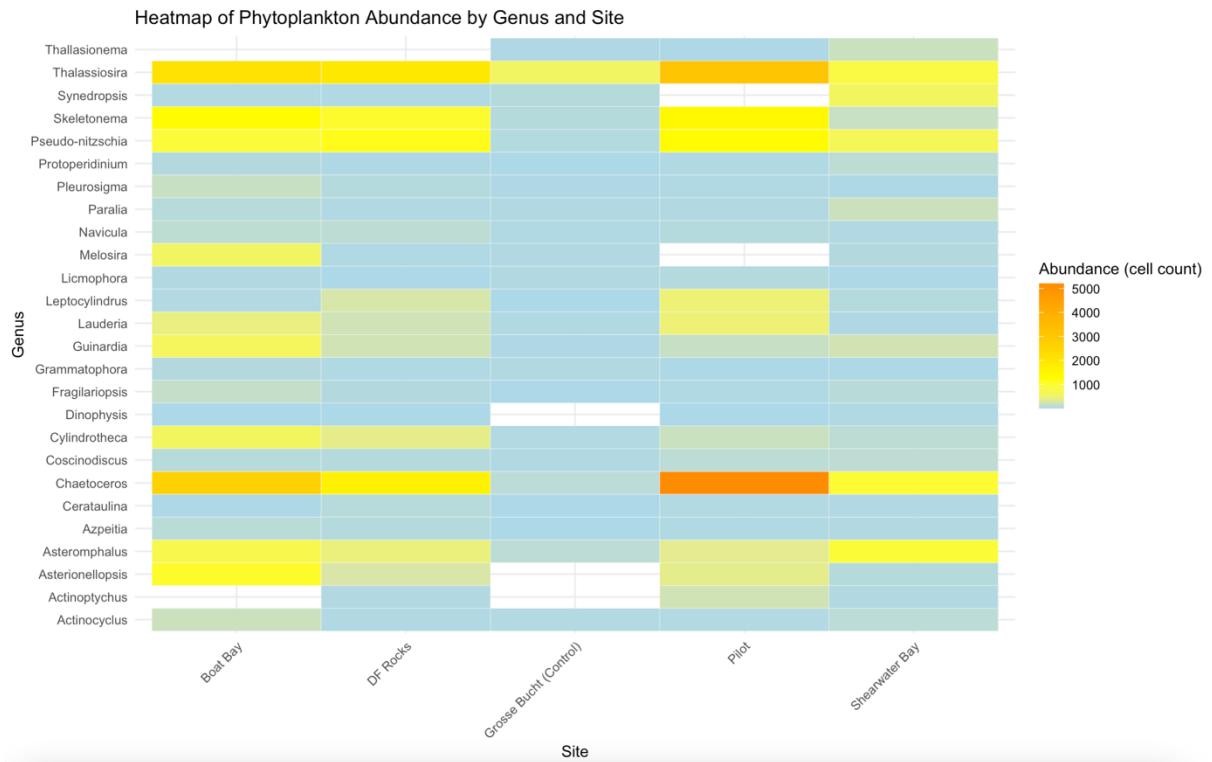


Figure 8: Heatmap of total cell count from 2022-2024 over different sites and genera

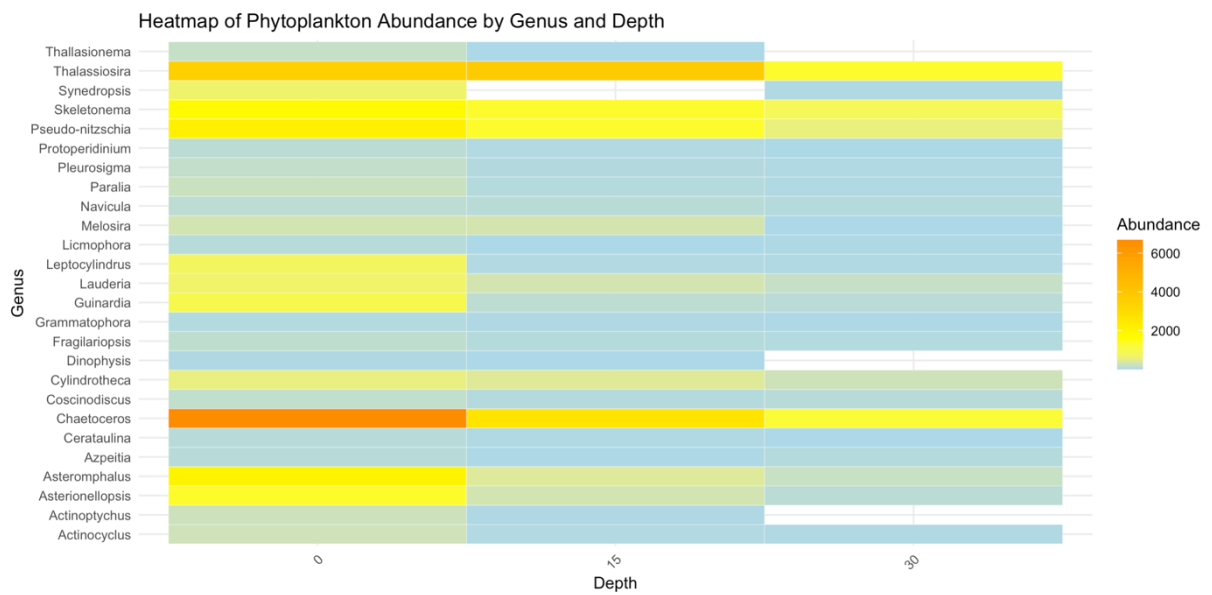


Figure 9: Heatmap of total 2022-2024 over different depths and genera

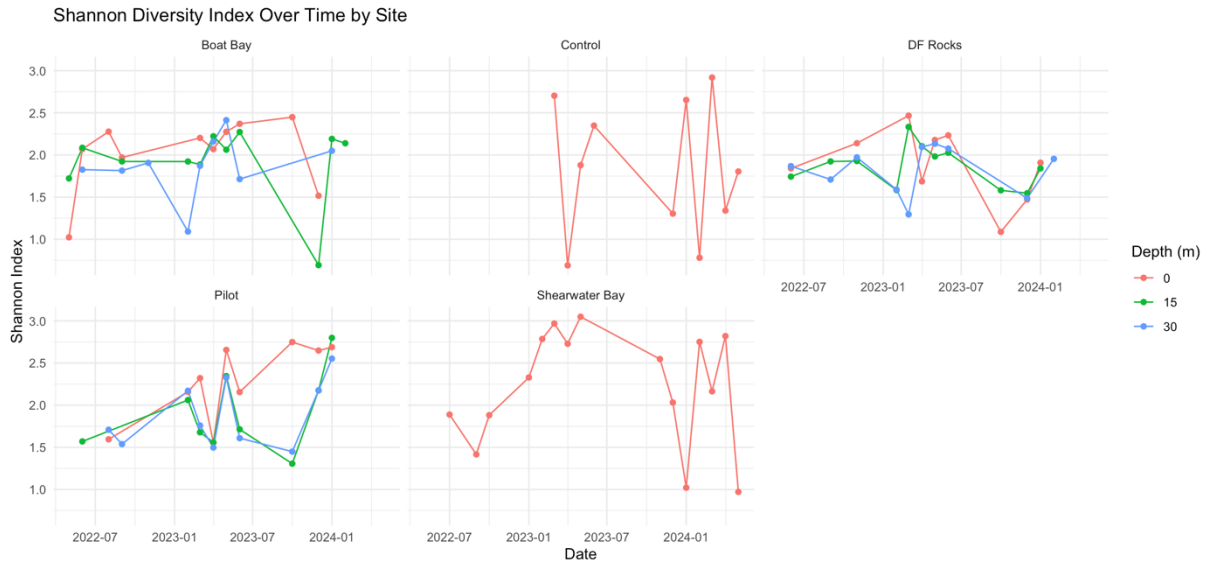


Figure 10: Shannon diversity over time by different sites and depths



Figure 11: Simpson Index over time by different sites and depths

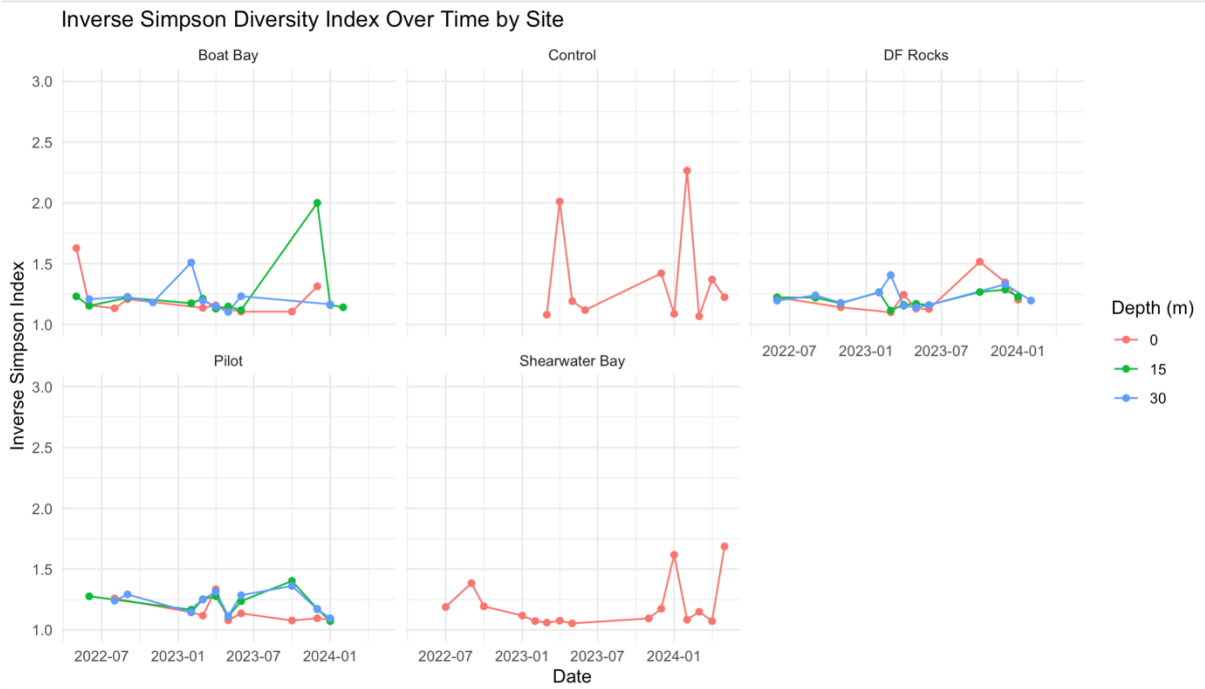


Figure 12: Inverse Simpson over time by different sites and depths

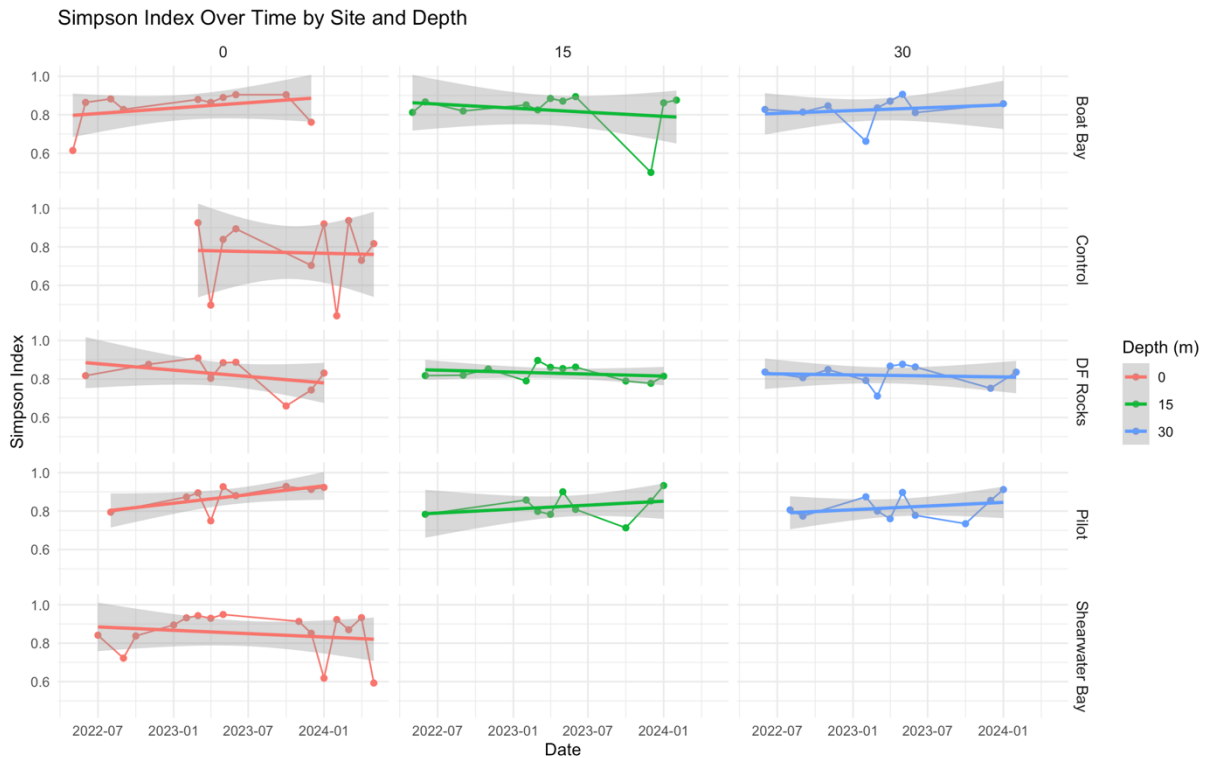


Figure 13: Linear model of Simpson Index over time by different sites and depths

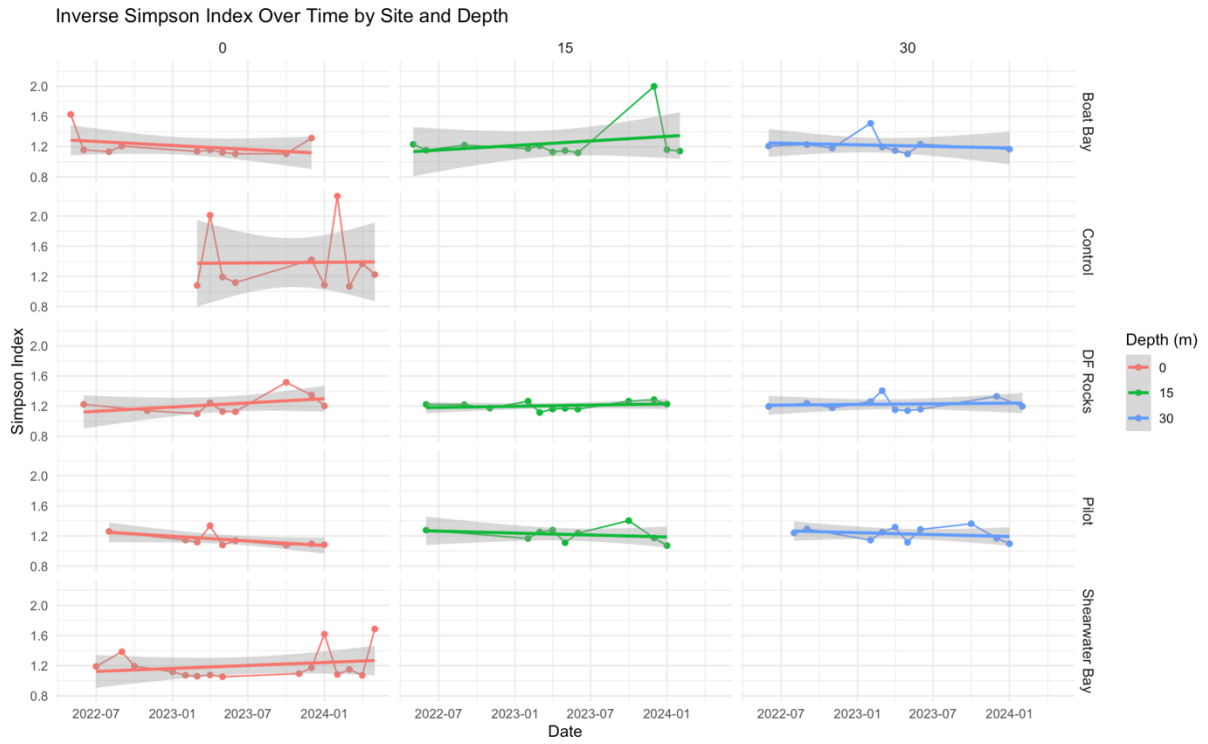


Figure 14: Linear model of Inverse Simpsons index over time by site and depth