

## **Seasonality of the Deep Sea ~ Bamboo Corals**

**Caroline Edmonds, University of Hawai'i at Manoa**

*Mentors: Dr. Fanny Girard, Dr. Steve Litvin, and Dr. Jim Barry*

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### **ABSTRACT**

Deep sea organisms' ecology is poorly understood. With the rising threat of deep-sea mining, climate change, and ocean acidification, understanding phenological changes in benthic species behavior and community composition is crucial. Technological development now allows for non-invasive long-term, high-resolution monitoring of deep-water sponge and coral gardens. A timelapse camera system was positioned in a deep-sea coral garden on Sur Ridge in Monterey Bay National Marine Sanctuary from June 2021 to June 2022. The system captured hourly photos of multiple coral species and associated fauna, totaling 9,470 images. Fifteen percent of the total images were randomly selected for manual annotation to determine the feeding state of bamboo corals and the abundance of megafauna. *Keratosia* were feeding the majority of the time minus a non-feeding period in mid-autumn. Coral predators demonstrated prey partitioning, *Coryphaenoides* showcased a seasonal trend, and species richness is visually linked to net primary productivity. This study offers insight into changes in bamboo coral feeding behavior and megafaunal phenology, highlighting the need for further research into the seasonality of megafauna and bamboo coral ecology.

## INTRODUCTION

The deep sea is one of the least explored environments on Earth. Many areas of the deep-sea fall under the UN's classification of vulnerable marine ecosystems (VMEs) due to the presence of slow-growing habitat-forming fauna providing unique habitats that are highly vulnerable to human activity due to slow recovery ability and lack of information (Ardron et al. 2014). Therefore, understanding the temporal changes of deep-sea faunal assemblages is critical to mitigating threats of climate change, ocean acidification, deep-sea mining, and bottom trawling (Levin and Bris 2015).

There is a strong correlation between surface processes and deep-sea ecosystems as deep-sea organisms primarily rely on food produced at the surface. Ecosystems like seamounts and canyons often enhance productivity (due to unique hydrodynamics) they often host high densities of deep-sea corals and sponges (Ramirez-Llodra et al. 2010). Biological structures like deep-sea corals help to increase species diversity by providing homes and food to sessile and mobile species (Buhl-Mortensen et al. 2010). However, environments like coral gardens are under threat.

Numerous factors affect deep-sea fauna assemblages. Bottom trawling removes much benthic fauna like deep-sea coral resulting in rapid declines of biodiversity and abundance of benthic communities. Because they provide structure and habitat for numerous species, losing this structure would lead to a functional loss in the ecosystem (Clark et al. 2016). Potential future threats include deep-sea mining. A recent study showed that benthic communities appeared visually altered by a disturbance test in the Okinawa Trough off of Japan, a potential area of seafloor massive sulfide mining. Nanofauna and meiofauna took several weeks to show signs of recovery and did not return to normal stages for a year, but macrofauna needed at least three or more years to start to show signs of recovery (Washburn et al. 2023). With deep-sea corals that grow at slower rates than nematodes or polychaetes, the recovery time could be even longer. Deep-sea ecosystems help regulate climate change through storing heat and carbon dioxide but, increased rates caused by warming, acidification, and larger deoxygenation zones near deep-sea benthic habitats may result in the loss of services provided by these ecosystems. Losing benthic habitats leads to decreased food availability and habitat.

Climate change in particular is expected to significantly impact deep-sea coral ecosystems. For example, theoretical models reveal a large decrease in the abundance of scleractinian coral (*Lophelia pertusa*) – 79%, octocoral *Paragorgia arborea* – 99%, and fish (20-30%) under different future climate scenarios (Morato et al. 2020). Boolukos et al. 2019 showed tangible decreases in biodiversity and cold-water coral occurrences due to increased temperatures. Diversity indices were higher in 2011 than in 2015, and by 2019, *Madrepora oculata*, scleractinian coral was nearly absent. With critical habitat for other fauna missing, biodiversity, abundance, and species distributions were heavily altered. Understanding natural changes in species behavior and community dynamics through time, in relation to environmental variability, would allow us to better predict the future impacts of climate change and thus make informed decisions for the management of these species.

Monitoring is critical in managing and understanding marine ecosystems (Vierod et al. 2014). Since so little of the ocean has been explored (less than 90%) it is extremely important to continually expand the baseline data for deep-sea ecosystems. In particular, monitoring can quantify the biodiversity changes over time and better help scientists tease out the effects of natural changes versus human activity (Magurran et al. 2010). There is a wide range of technology available for monitoring deep-sea ecosystems including a wide range of autonomous vehicles (AUVs), remotely operated vehicles (ROVs), benthic rovers, wave gliders, timelapse camera systems, among other benthic observatories (MBARI, 2023). Image monitoring can help to assess the health of coral reefs and ideally prevent major disturbances like at the Darwin Mounds in the Northeast Atlantic. The Darwin Mounds were closed after severe damage from anthropogenic activities. Monitoring the system showcased low resilience rates and slow recovery potential for deep sea ecosystems (Huvenne et al 2016). Monitoring any benthic region is important to understand recovery processes following impact and characterize ecosystem dynamics in relation to environmental change.

Phenology is defined as the timing of cyclical biological events. Biological rhythms are defined as “cyclic changes in an organism’s biology, ranging from behavior to rhythms in physiology and gene expression” and endogenous oscillators are, “an internal timing mechanism that is self-sustained but can be entrained by environmental cues”

have been evidenced in many marine environments (Hafker et al. 2022). Phenology in fish has been the most well-studied across numerous types of oceanic ecosystems. From estuarine and wetland fish, subtidal zones fish, and pelagic and demersal fish in temperate waters, all species showcased seasonal trends validated by biomass, composition, abundance, and diversity metrics (Da Silva et al. 2010, Hagan and Able 2001, Hyndes et al. 1999, Masuda 2008, Potter et al. 1986). Fish are not the only organism demonstrating phenology in their respective ecosystem. Arthropods and macroinvertebrates in wetlands revealed cycles even with high particulate food available all year round (Majeed et al. 2020, Neckles et al. 1990, Bauer 1985).

Similarly, phenology has been identified in the deep sea. In the deep sea, known biological rhythms drivers include seasonal changes in particulate organic carbon (POC) and tides. In temperate latitudes, a seasonal pulse of spring bloom and summer activity directly links surface primary production and the deep-sea benthos, supplying a periodic food source for benthic communities (Bilett et al. 1983). Megafauna and higher population-level feeding activity have been shown to be significantly higher during POC summer events along the benthic shelf community in the West Antarctic Peninsula (Sumida et al. 2014). Upwelling coupled with seasonal increases in surface primary productivity and carbon flux, increases organism biomass and density in the Monterey Bay area along the California Current (Pennington and Chavez 2000). In this region, a seasonal input of POC covers the deeper depths of the bay during the spring and summer, and occasionally in the fall (Pennington and Chavez 2000). A study conducted by Froe et al. 2022, demonstrated small phytodetrital particles supply high-quality food via internal waves powered by tides. These waves and shoaling mechanisms include nutritious zooplankton fecal pellets and previously formed fast-sinking aggregates right above the cold-water coral community.

Recent studies have shown POC, tides, and other environmental factors affecting temporal dynamics in deep-sea megafauna. Megafauna community exhibited seasonal patterns at various depths and habitat types in a multi-year study on the western coast of Canada. The group discovered that factors linked to seasons or tides, including boundary layer currents, temperature, and surface chlorophyll concentrations influenced community dynamics. Some of these changes may have been driven by the species'

behavior. The strength and speed of currents can alter megafauna (deep sea fish, crawling crabs, and snails) locomotion capabilities (Aguzzi et al. 2010 and Aguzzi et al. 2011). Additionally, changes in surface primary production can influence deep-sea communities. One fish species, in particular, has been studied in depth for seasonality in the deep sea. Grenadiers (*Coryphaenoides*) have an uptick in abundance in correlation with the seasonal fluxes of POC following their prey taxa, echinoderms (Bailey et al. 2006 and Priede et al 1994). Moreover, a bait trap study showed seasonal changes in multiple fish scavenger species across different regions, in which the study deemed to be related to the alterations in the surface productivity of the above water column (Janßen et al. 2000).

More recent phenology studies have used non-invasive approaches in Monterey Bay National Marine Sanctuary. A study by Girard et al. in 2022 characterized the seasonality of the octocoral, *Paragoria arborea*, and its feeding patterns. The authors showed that feeding varied with season, with a dormancy period from January to early April (period of low primary productivity) and tides through changes in bottom current speed and direction. Similar factors, including primary productivity and particle density in the water column affecting food availability, also led to cyclic changes in the diversity and abundance of fauna living in this coral habitat (Girard et al. 2023).

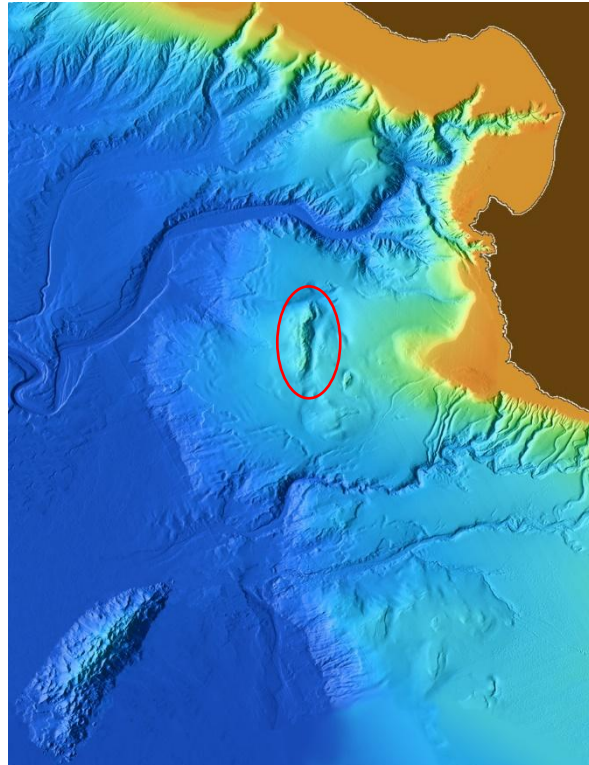
Focusing on images collected by a time-lapse camera deployed in a deep-sea coral ecosystem at a depth > 1000 m in Monterey Bay National Marine Sanctuary from June 2021 – June 2021 the goal of this study is to answer three major questions: 1) Do bamboo corals exhibit seasonality of feeding showcased via polyp activity? 2) Does megafauna community composition change over the course of 9 months? 3) What environmental factors could be impacting seasonality changes if any?

## **MATERIALS AND METHODS**

### **2.1 Study area**

This study focuses on Sur Ridge, ranging 800 –1500 m deep, south of the deep Monterey Canyon (Figure 1). To better understand the Sur Ridge region, a timelapse camera system facing different coral colonies, along with current sensors was placed at 1230 meters along the northern region of Sur Ridge. A similar project was conducted on the same section of Sur Ridge but focused on a different species, *Paragoria* sp. The camera system

was positioned to include five bamboo corals, four *Keratoisis*, and one *Isidella tentaculum* (See Figure 1). The timelapse camera allows for remote observation of the feeding behavior of the corals and passing megafauna to attempt to identify potential seasonal patterns over the course of a nine-month time period.

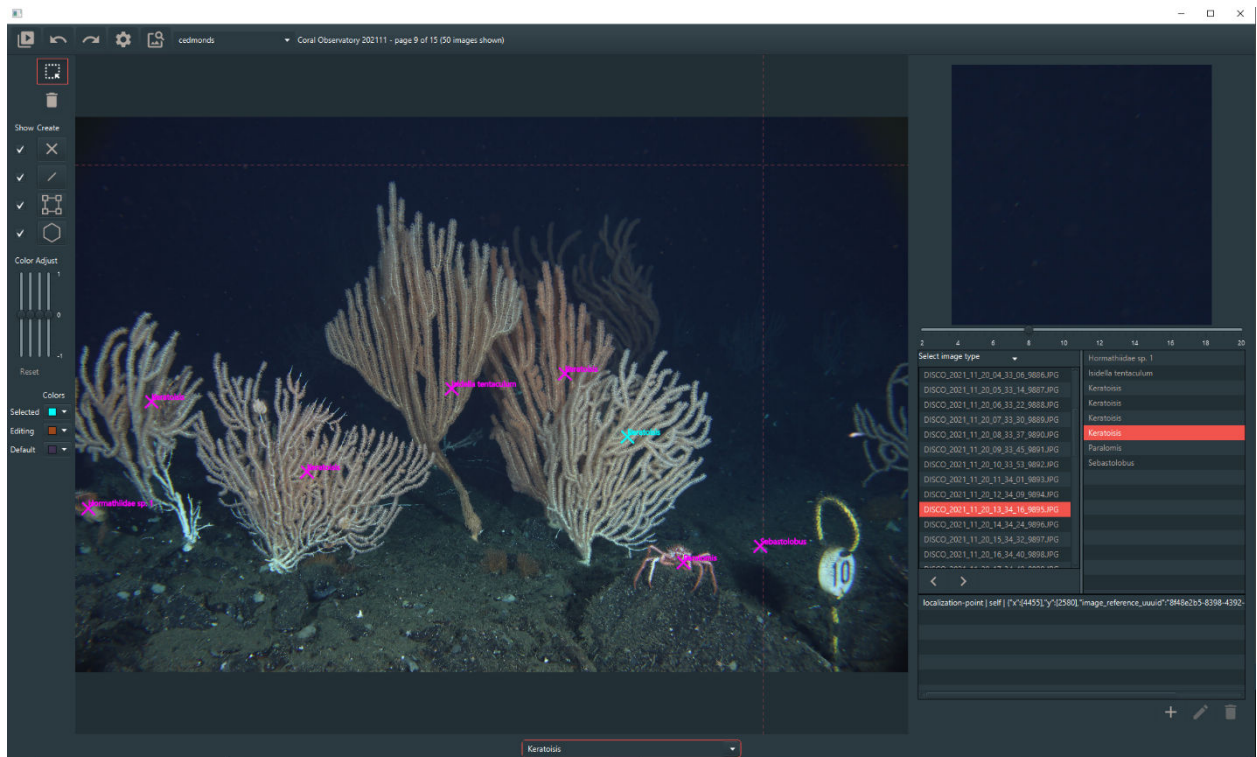


**Figure 1.** The study area of the project and time-lapse camera view. Sur Ridge is circled in red on the map.

## 2.2 Image collection and annotation

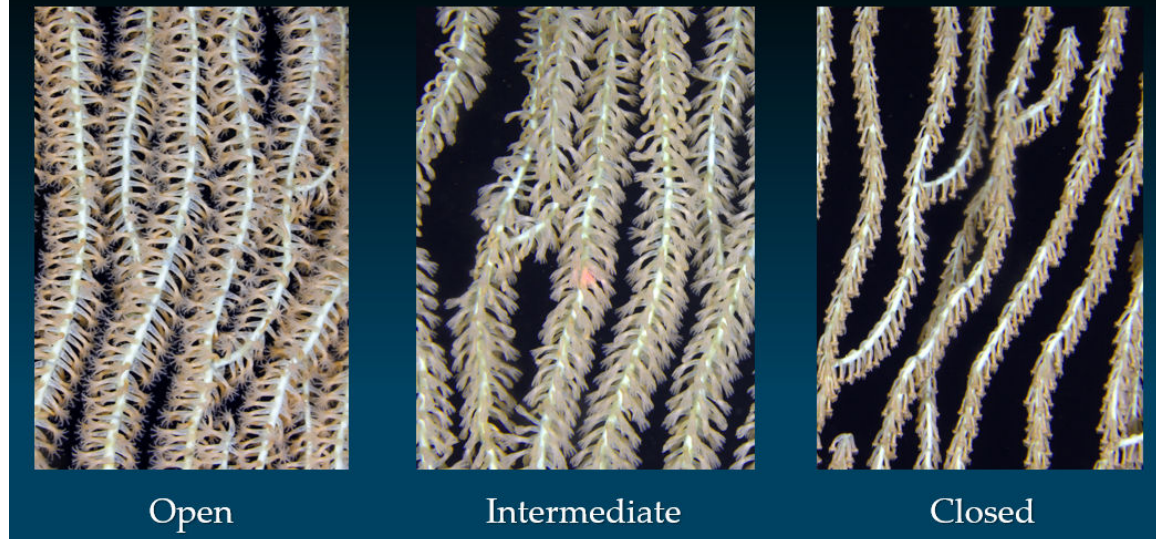
A time-lapse camera with strobe lights mounted on a frame took images every hour. Images were taken with a Canon EOS 5D Mark IV at f/10 1/20 sec ISO 400 creating a 6720 x 4480 72 dpi 24 bit output. A total of 9,470 images were taken and downloaded over the course of a year (June 2021 to June 2022). Due to time constraints, 15% of the total images for 9 months were annotated, representing 887 photos. Images were randomly selected based on an R-sampling script (RStudio, 2020) and annotated using the software Mondrian v.1.1 (Figure 2). This is the first-ever case of usage of the software and is still under development. The number of images per month ranged from 67 to 111 to best understand seasonality over the time period. Each image was analyzed three times. First, all visible megafauna were identified using the Sur Ridge Field Guide

(Burton et al. 2017) and MBARI's Deep Sea Guide. This left out the top fourth of the image because species swimming in this section of the photo could not be identified consistently, reducing the total pixel size from 6720 x 4480 to 6719 x 3939. In the next round, four corals and one sea anemone had associations added for three stages of feeding, open, intermediate, or closed (Figure 3). Opens polyp(s) assume the organism is feeding and closed and intermediate reflected no feeding. The last time looking at images was to ensure all fauna were correctly labeled, association comments were accurate, no missing species, and all images were complete for data extraction.



**Figure 2.** Screenshot of Mondrian v.1.1 annotation process of sample timelapse image.

## Coral Feeding Behavior Categories



**Figure 3.** Identified feeding states of bamboo corals; from left to right open, intermediate, and closed.

The automated detection and identification feature based on AI algorithms developed at MBARI was also tested on 2 months' worth of images to evaluate its accuracy. The current algorithms never created a bounding box around all 5 coral colonies and sea anemones. Tweaking the photos' exposure and color had little effect on what the algorithms identified.

### 2.3 Data Filtering and Analysis

The localization and comment data were extracted and run through scripts in RStudio to create four matrices: *Isidella tentaculum* feeding, *Keratoisis* feeding, Hormathiidae sp.1 feeding, and a fauna abundance matrix.

The packages used in R included: `vegan`, `tidyverse`, `ggpubr`, `ggplot2`, `xts`, `dygraphs`, `htmlwidgets`, `RColorBrewer`, `gtable`, `grid`, and `lubridate`. Time series of coral feeding and species abundance were analyzed to assess seasonality. Most abundant fauna was defined by the highest number of observations over the course of 9 months where 5 species represented 79.15% of all the photos. Using the `vegan` package, the time series of species richness were also computed. A principal component analysis (PCA) was created using the Bray-Curtis transformation for the monthly average observation matrix. Net primary production data for correlation data was gathered via a portal sponsored by



Oregon State and NASA (obtained from:

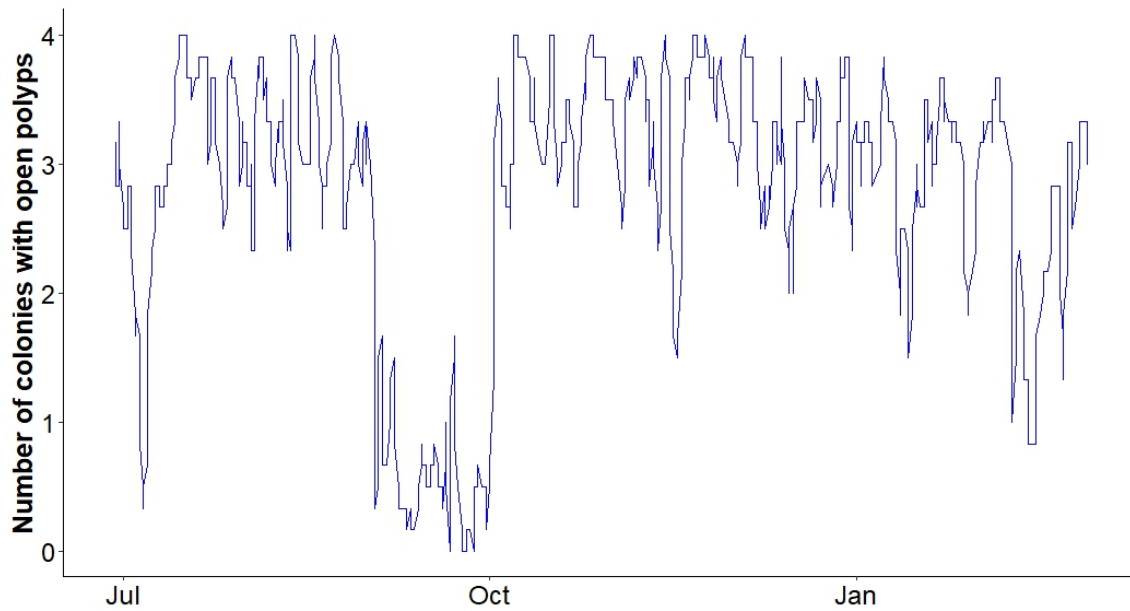
<http://orca.science.oregonstate.edu/1080.by.2160.monthly.hdf.vgpm.m.chl.m.sst.php>.)

The NPP monthly average was derived from the June 2021 – February 2022 data files from the website. Current data for further environmental analysis was obtained from MBARI's acoustic Doppler current profiler (ADCP), a hydroacoustic current meter. Data was pulled from the two closest current meters around 3-5 meters above the ridge's bottom over the course of the project timeline.

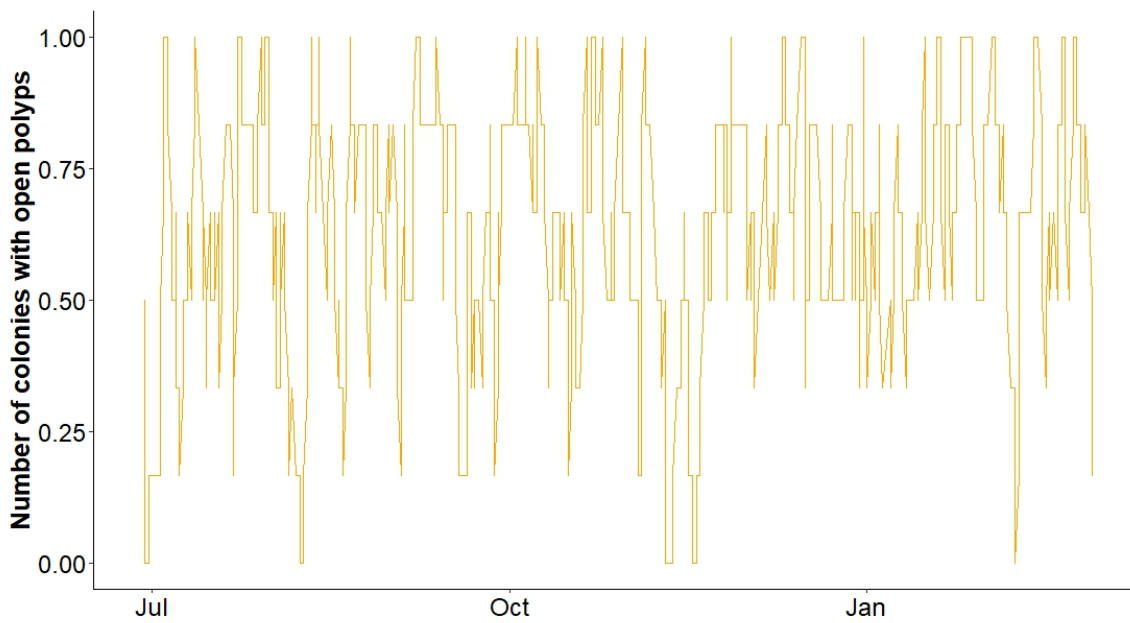
## RESULTS

### 3.1 Changes in Coral and Sea Anemone Feeding Behavior

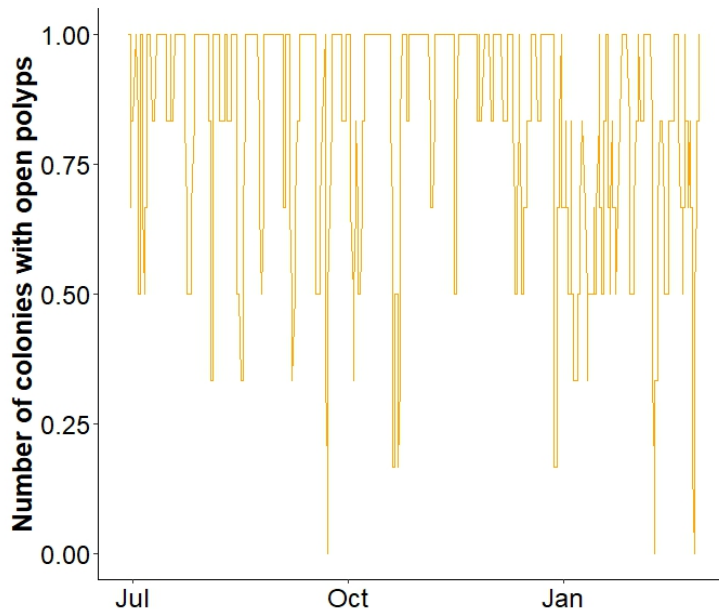
Overall, of the three species tracked, *Keratoisis*, *Isidella tentaculum*, and Hormathiidae sp. 1, only *Keratoisis* demonstrated a clear closed period from this resolution of data. *Keratoisis* included 4 colonies across the camera's frame. All the colonies were feeding the majority of the time from June 2021 to February 2022 (Figure 4). There was a dormant period where only one colony was feeding from late September to mid-October. Visual observations showed that the two *Keratoisis* colonies on the right of the image were observed more in intermediate and closed states than the other two colonies on the right side of the *Isidella tentaculum* (see Figure 3). The one large colony of *Isidella tentaculum* appeared to have a cyclic behavior (Figure 5). Hormathiidae sp. 1 showed a high number of intermediate states compared to *Isidella tentaculum* (Figure 6). Visually the sea anemone seemed to follow the furthest left *Keratoisis* colony in regard to feeding behavior. This would need to be investigated further to better tease apart the cause.



**Figure 4.** Moving average of feeding behavior states of 4 colonies of *Keratoisis* over the course of 9 months with 15% of images annotated



**Figure 5.** Moving average of feeding behavior states of 1 colony of *Isidella tentaculum* over the course of 9 months with 15% of images analyzed.



**Figure 6.** Moving average of Feeding behavior states of one Hormathiidae sp. 1 over the course of a 9-month period with 15% of images annotated.

### 3.2 Changes in the Faunal Community

Over 9 months a total of 22 taxa were observed over 1,938 observations. The top 5 taxa, *Coryphaenoides*, *Laetmogone*, *Pandalus amplus*, *Sebastolobus* spp., *Neolithodes* sp. made up 79.15% of all the observations. However, I will focus on *Coryphaenoides*, *Sebastolobus* spp., *Solaster* sp. (35), *Dipsacaster* (56), *Tritonia* sp. (46), *Neolithodes* spp., *Paralomis multispina*, and *Pandalus amplus* for the following analyses based on ecological role and abundance. These taxa represent 74.45% of the total observations and most were part of the top 10 most abundant species (Table 1).

**Table 1.** Total Counts for Top 10 abundant species grouped by phyla – total images = 887

Species	Count
<i>Coryphaenoides</i>	446
<i>Sebastolobus</i> spp.	242
<i>Microstomus pacificus</i>	26
<i>Solaster</i> sp.	35
<i>Dipsacaster</i> sp.	56
<i>Neolithodes</i> spp.	176
<i>Paralomis multispina</i>	171
<i>Pandalus amplus</i>	271
<i>Laetmogone</i>	399
<i>Tritonia</i> sp.	46

The top 5 most abundant species showcase high abundance in the summer months, a low point in December, and another increase in January and February (Figure 7). The top 5 species and total observations were, *Coryphaenoides* (446), *Laetmogone* sp. (sea cucumber – 399), *Pandalus amplus* (Northern shrimp – 271), *Sebastolobus* spp. (Thornyhead – 242), and *Neolithodes* sp. (king crab species – 176).

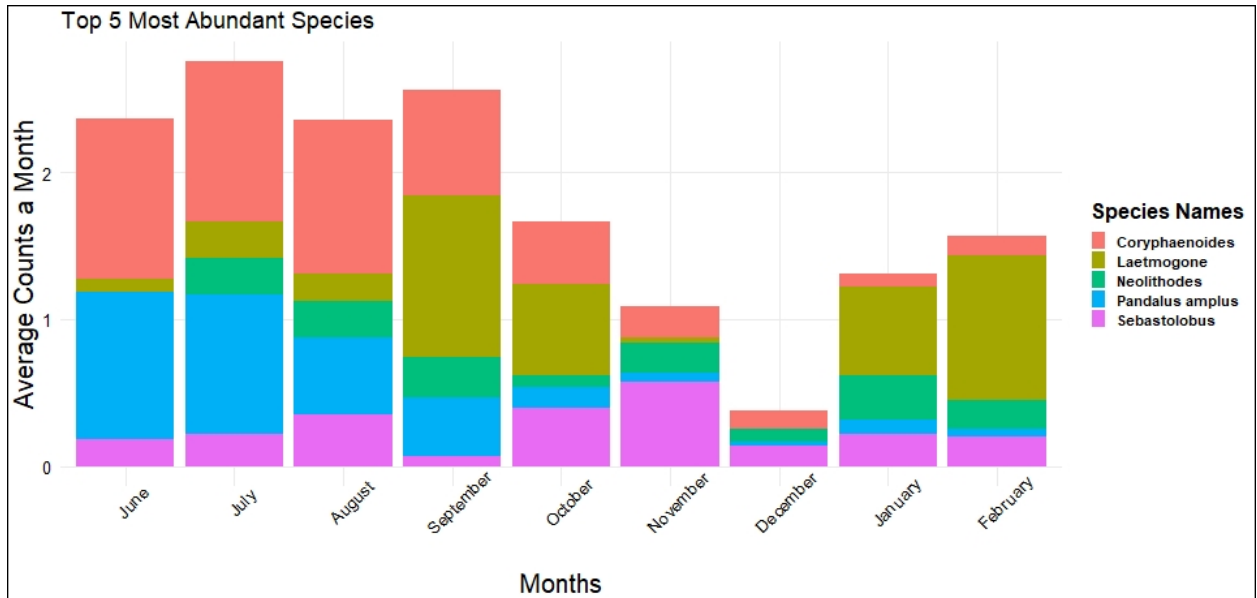
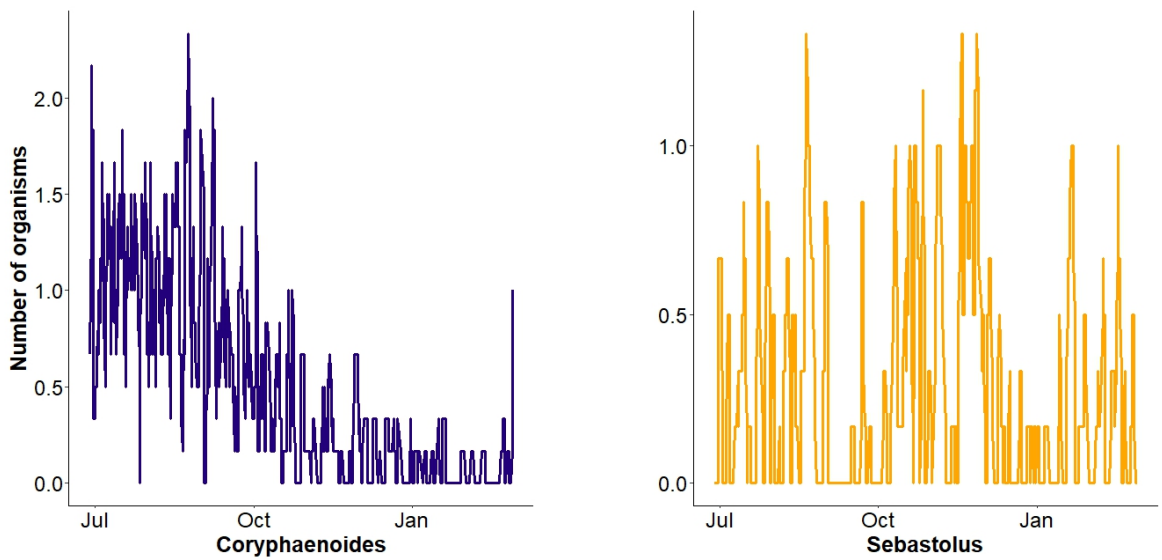


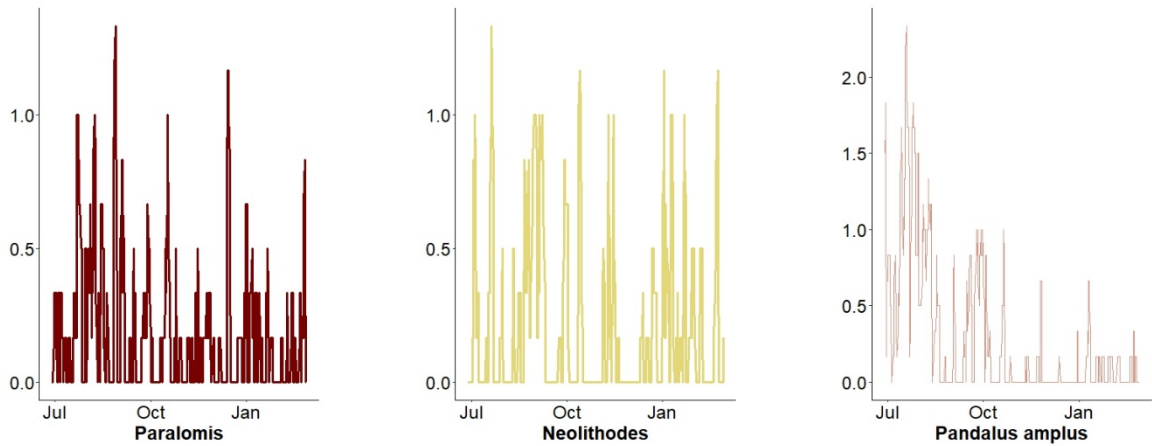
Figure 7. Top 5 most abundant species monthly observations across 9-month time span.

### Fish and Arthropod Species

The *Coryphaenoides* had the most distinct seasonality out of the fauna and the highest observation count at 446. It was high in abundance in the summer months, June to late August, and decreased linearly until the winter months when it was rarely observed (Figure 8). In the summer months, groups of up to 7 were observed and as low as one. *Sebastolobus* spp. pattern was not clear with about half of the total observations at 242. There were in high abundance in the summer months, November, and December, and again another spike in February. Further image analysis may show smaller cyclic patterns of these fish. Both short-spined and long-spined were included in this classification of *Sebastolobus* spp. (Figure 9).



**Figure 8.** Fish observation frequency of Pacific Grenadier (*Coryphaenoides*) and Thornyheads (*Sebastolus* spp.) over a 9-month period.



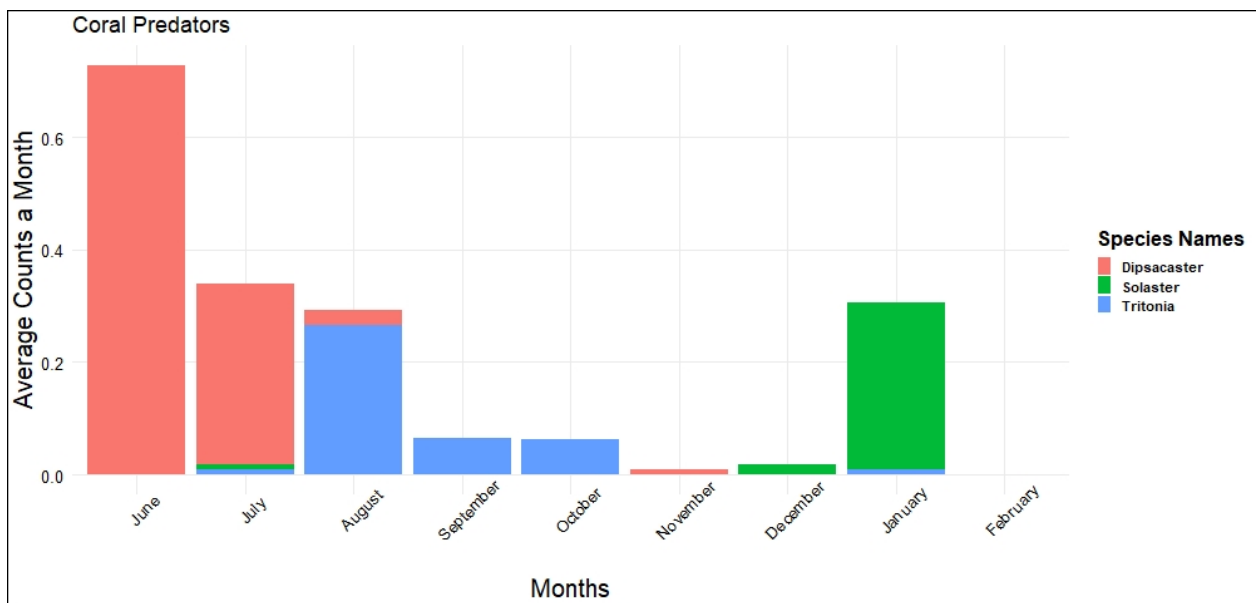
**Figure 9.** Arthropod observations over 9 months; from left to right *Paralomis multispina* (King crab species 1), *Neolithodes* sp. (King crab species 2), and *Pandalus amplus* (Northern shrimp).

The king crab species, *Paralomis multispina* and *Neolithodes* sp., and shrimp *Pandalus amplus* were some of the most abundant fauna observed behind the fish species at 171, 176, and 271 total observations over the course of 9 months. *Paralomis multispina* peaked in the summer months and slowly decreased into the winter months but had a large spike in late December (Figure 9). The majority of these observations show that this species was almost always walking by the coral but not on the coral itself. The opposite was true for *Neolithodes* sp. which were almost always on the same *Keratoisis* colony, the furthest to the right of the image. The time series demonstrates a

sinusoidal pattern with peaks in later summer and later winter months (Figure 9). *Pandalus amplus* demonstrated a similar pattern to *Coryphaenoides* with the highest abundance in the summer months and teeters off into the winter months. The shrimp was commonly observed next to the sea anemone on the far left of the image and occasionally under the *Isidella tentaculum*.

### Coral Predators

Figure 10 demonstrate coral predators of the bamboo coral abundance over time. Each of the three species *Dipsacaster* sp. (sea star), *Solaster* sp. (sunflower sea star), and *Tritonia* sp. (nudibranch) had very little overlap of occurrences. Only the month of July had all three species along with August and January with two of the three species present. Note these species were only observed on the *Keratoisis* colonies and never the *Isidella tentaculum*. These species only appeared on the two colonies to the left of the *Isidella tentaculum* while the crabs were almost always on the right two colonies.

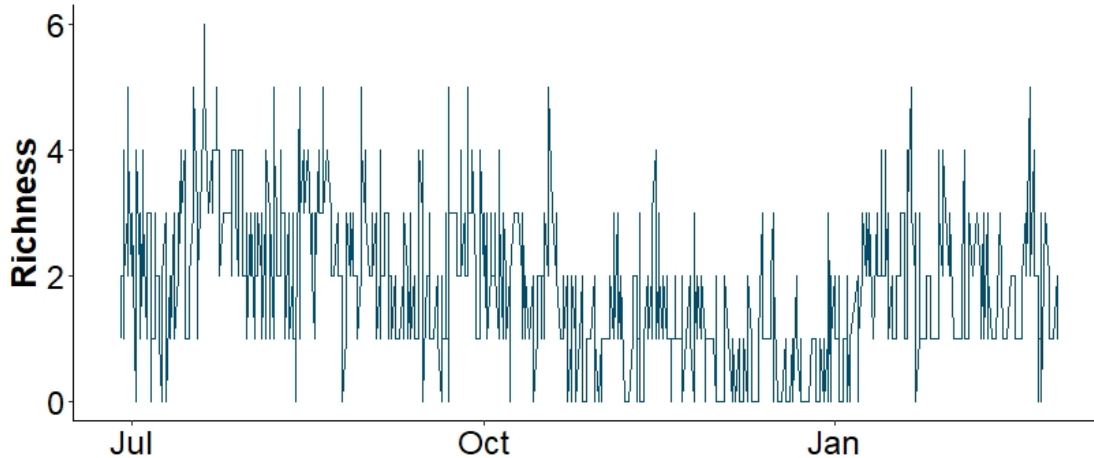


**Figure 10.** Coral predators’ average count per month over the course of 9 months.

### Changes in diversity and Community Structure

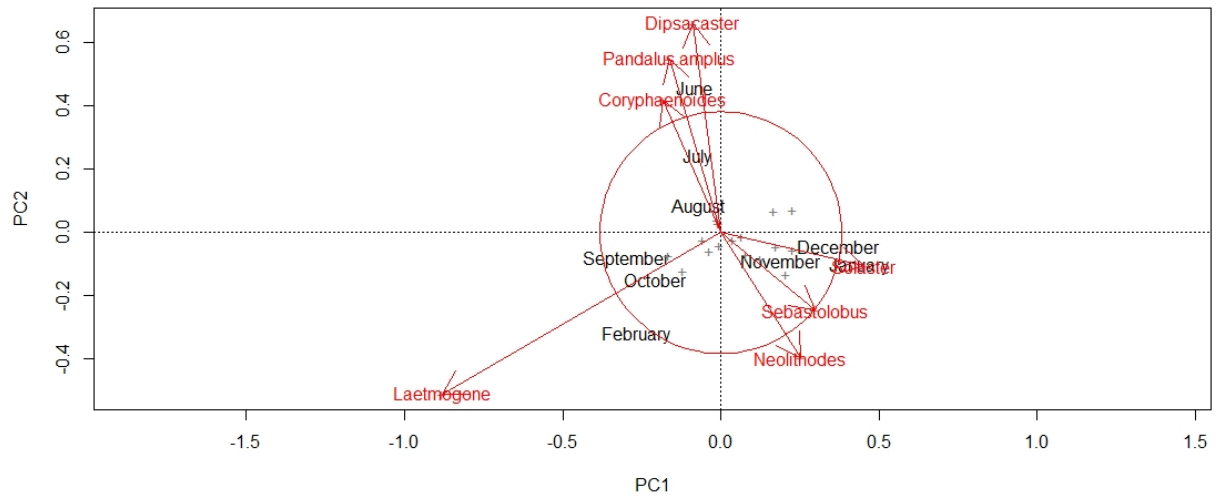
Species richness showed general expected seasonal trends. There was a higher number of species observed in the summer to late fall months (June to October). Fewer

species were observed in the winter months of November and December, but the variety of species increased from January to February (Figure 11).



**Figure 11.** Species Richness in a time series including all species observed.

The PCA reveals month groupings were primarily dictated by two species. The presence of *Dipsacaster* sp. in the summer months grouped June, July, and August together in one quadrant. The winter months, November, December, and January were grouped together with *Neolithodes* sp. being very abundant in this time period. However, one winter month, February, was grouped with the fall months of September and October. But the large abundance of observations of *Laetmogone* grouped September, October, and February together (Figure 12).



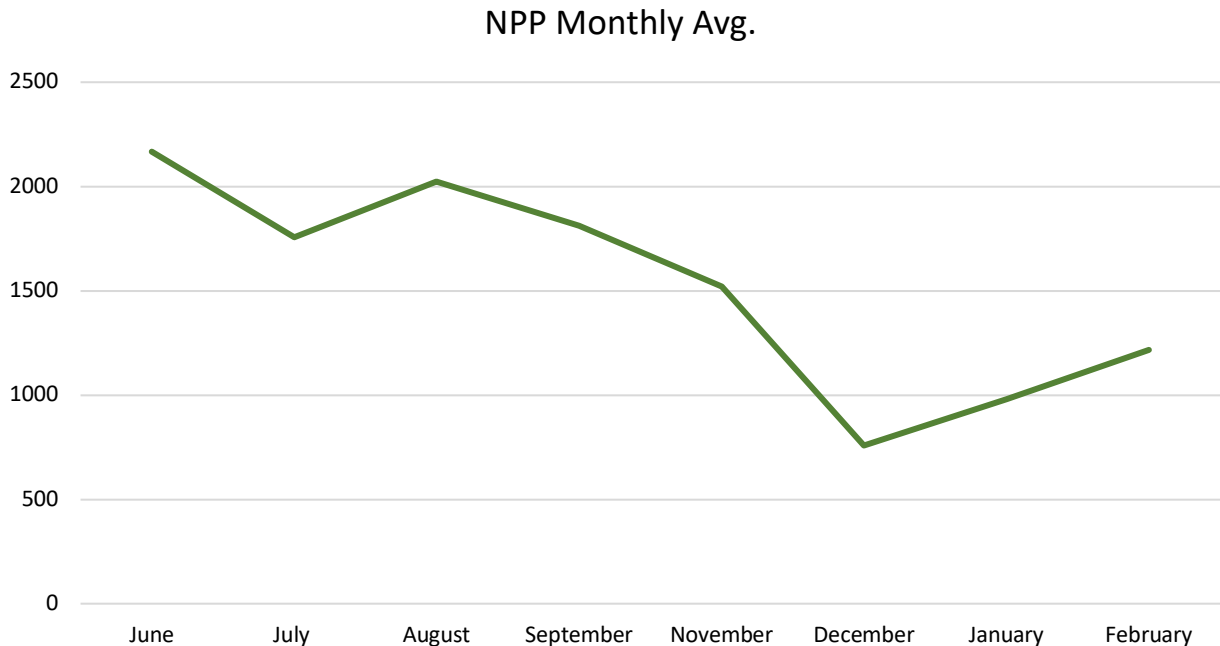
**Figure 12.** PCA of all 9 months with contribution circle. Only taxa that contribute the most to the variability between months (outside the circle) are represented.

### 3.3 Environmental Correlations

#### Net Primary Productivity

The net primary productivity showed a similar pattern as species richness and the top 5 most abundant species in a time series (Figure 13). Net surface primary productivity served as a food proxy in this context. Higher net primary productivity levels were associated with periods of higher species richness and a higher number of average observations. Vice versa months with lesser “food” observed lesser species richness and total observations. A spike in net primary productivity could be the reason for the increased number of observations and species richness leading to February being grouped with the fall months as the level of NPP was only within a couple hundred off of September (Figures 12 & 13).





**Figure 13.** Average net primary productivity. Monthly averages from Oregon State and NASA satellite data: [Ocean Productivity: NPP Products \(oregonstate.edu\)](http://Ocean Productivity: NPP Products (oregonstate.edu))

### Currents

Due to time constraints, current speed, direction, and echo were briefly analyzed. For *Keratoisis* and *Isidella tentaculum*, the upper and lower limits for speed, direction, and echo averages all had zero distinct ranges without overlap of values and did not appear significantly correlated to feeding behavior.

## **DISCUSSION**

Four of the five bamboo colonies, *Keratoisis*, were almost always feeding throughout the course of 9 months. There was only a small portion in early October when none of the colonies were feeding. Similarly, the *Isidella tentaculum* coral colony and Hormathiidae sp. 1 anemone showed no seasonal patterns. The lack of seasonality was surprising as other studies showed strong seasonality in feeding activity for other coral species including a study on *Paragoria arborea* colonies only a few meters away from this study site. Further image analysis could shed light on finer-scale cyclic patterns, such as periodicities related to tidal motions.

Another reason why the lack of seasonality was unanticipated was upwelling patterns. Upwelling is critical in connecting surface primary production to the deep sea. Upwelling brings cold nutrient-rich water to the surface allowing for greater primary production

which in turn leads to more POC (particulate organic carbon) sinking to the deep sea, fueling these benthic communities. In the Monterey Bay region, primary production is high in the summer months and low in the winter months therefore one would expect fewer “open” feeding behavior observations in the winter months with less food transported to the deep-sea. Upwelling could also impact the benthic community structure in terms of currents and available food.

There was distinct seasonality in the abundance of the Pacific Grenadier (*Coryphaenoides* spp.). The species abundance spiked in the summer months and slowly declined until November when there were very few observations for the rest of the studied period. It appeared to positively correlated to the average monthly net primary productivity or the “food” as the “food” followed a similar decreasing pattern into mid-November. The coral predators, *Dipsacaster* sp., *Tritonia* sp., and *Solaster* sp., feed on only *Keratoisis*, never *Isidella tentaculum*, and were never on the same colony. Furthermore, the predators hardly ever overlapped with each other. *Dipsacaster* sp. was most abundant in the summer months, *Tritonia* sp. was most abundant in late summer and early autumn, and *Solaster* dominated the winter months. With very little overlap these predators may demonstrate prey partitioning, or only one predator feeding on a food source at a time to reduce competition. Note there is no scientific literature analyzing *Dipsacaster* sp. stomach contents, so it is not known if it feeds on *Keratoisis*. However, visual observations within the timelapse photos show the sea star in an arch position on the *Keratoisis*, commonly associated and seen with feeding behaviors in other predatory sea stars. Visually there was a positive correlation between the monthly average net primary productivity, or the food proxy, and overall species richness. When the food proxy levels were high in the summer months the number of species observed was also. This evidence supports previous studies of seasonality conducted in the Barkley Canyon of Canada (Matabos et al. 2014 & Chauvet et al. 2018). Even with a slight peak of food in the typical barren month of February, there was an uptick in the number of species observed. Due to time constraints, no correlation analyses were conducted with species richness and net primary productivity.

Hormathiidae sp. 1’s feeding behavior needs further exploration. Visually the large sea anemone appeared to mimic the *Keratoisis* next to it looking at the time series

the similarity did not hold true across all the *Keratosia* colonies. However, it was difficult to discern between open and intermediate feeding states which could shed bias into these results. The sea anemone had frequent arthropod visitors, especially in the summer months. Other studies have demonstrated arthropods have commensal and even mutualistic relationships with anemones which could be something to continue to track in the region. Rockfish *Sebastes* spp. were frequent visitors to the bamboo coral garden. The observations appeared cyclic but were not correlated to net primary productivity or currents. If more photos were analyzed, the species may demonstrate connections to lunar or tidal cycles. The current study could not give a fine enough scale to investigate these variables. Due to time constraints, current data was briefly investigated. Continuation of the project in the future could shed light on the influence of current speed and direction on bamboo corals feeding activity. As the *Paragorgia* sp. of the area prefer to feed during periods of strong westward flow, bamboo corals feeding may also be impacted by currents.

This is only the second species of deep-sea coral that has been analyzed for seasonality and feeding behavior at depths > 1000m. Due to the large differences in feeding behavior between bamboo coral and *Paragorgia* sp., a wider range of species needs to be studied worldwide to better understand coral garden ecosystem dynamics. Studying more species using imagery data could be more efficient if machine learning was incorporated. Manual annotation is labor-intensive and time-consuming but incorporating AI models that can automatically localize and identify species visible in images could allow for more video transects and other imagery to be processed faster in the near future. Hybrid methods of manual and model annotations are already being developed and tested at MBARI.

Further studying the seasonality of deep-sea corals and their associated fauna would help underline the biogeographical patterns worldwide. It could even identify key indicator species to better monitor and manage these critical deep-sea ecosystems. Also, a better understanding of the effect of natural environmental change on these ecosystems will allow us to better predict the future impacts of climate change. In particular, changes in NPP due to climate change could have a strong impact on deep-sea benthic communities.

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