MBARI Monterey Bay Aquarium Research Institute

Devoured or Dissolved: Using Time Series Imagery to Explore the Outcome of Deep Sea Detrital Aggregates

Fiona Ryan, University of Hawai‘i at Hilo

Mentor: Dr. Crissy Huffard

Summer 2024

Keywords: Carbon, Aggregate, Degradation, Megafauna, Sea Cucumber

ABSTRACT

Exploring the fate of carbon rich detrital aggregates exported from surface waters to the deep ocean is essential for understanding the role of the deep ocean as a carbon sink. This study focused on answering the question of aggregate fate once sunk. Using data from an abyssal time series site in the Eastern Pacific, I analyzed the residence time and degradation pathways of these aggregates during three significant carbon pulse events in 2007, 2014, and 2017. My findings reveal a relationship between residence time and dominant degradation pathway, with megafaunal degradation leading to a shorter residence time. The three pulse events differed in residence time and in degradation pathway. Sea cucumber density data from the area during those years also appeared to relate to the degradation pathways with more sea cucumbers present leading to more megafaunal consumption. With no data to determine the total volume of carbon entering the system a hue analysis was conducted to determine seafloor aggregate cover across

the three events which suggested that 2014, the event with the shortest residence time, had the most or the freshest aggregates.

INTRODUCTION

Phytoplankton, as primary producers in the ocean, play a crucial role in the marine carbon cycle. Once they die they form detrital aggregates, globs of carbon rich matter. These aggregates, once formed, often sink to the seafloor, where they are large enough to be visible to the human eye (Iverson 2023). Investigating the residence time of these aggregates on the seafloor can provide valuable insights into the environmental conditions at time of their deposition. The deep ocean, however, is not a static environment, with dynamic processes constantly reshaping the seafloor. A good example of this changing landscape is the influx of these carbon rich aggregates. A key unanswered question is what is happening to the aggregates once they reach the seafloor, are they more likely to be consumed by benthic megafauna or degraded through other biogeochemical processes?

The deep ocean is one of the planet's most significant carbon sinks (Sabine et al 2008, Zhang 2017, Raven 1999). Knowing how rapidly carbon is sequestered and whether this rate is constant or variable could provide interesting insights into the environment of the abyssal plain. The method of sequestration directly influences the long term storage of carbon and the global carbon cycle. We know that carbon makes its way to the seafloor in pulses (Smith et al. 1998) and that these pulses have been linked to increases in megafauna (Lemon et al. 2022). This increase in megafaunal species could have an effect on the rate of consumption and thus have implications for the rate of sequestration of carbon within the deep sea. Higher rates of carbon consumption by megafauna may lead to a smaller amount of material being sequestered within the sediments as some is lost through respiration.

This research project was undertaken through an internship with MBARI. This study leveraged data taken from three years at Station M, a long term monitoring station in the Eastern Pacific (Smith et al 2020), in order to investigate the fate and longevity of carbon rich detrital aggregates during high export pulse events. Holothurians play a crucial role in deep sea ecosystems (Gage &

Tyler 1991, Laureman et al. 1996, Ruhl 2007) and are likely major contributors to aggregate degradation. Previous studies at Station M have shown that between 2007, 2014, and 2017, the years in which this study takes place, 2014 displayed the highest number of sea cucumbers (Lemon et al. 2022). With a high density of sea cucumbers present in the area I hypothesize that aggregate residency time will be shortest in 2014, and I expect the dominant method of degradation across all three years to be megafaunal consumption due to the high carbon nature of the three periods.

.

METHODS AND MATERIALS

Study Site

Station M is at ≅4000m depth 291 km offshore off the coast of Central California. This site was chosen as a long term monitoring site due to its high seasonal fluctuations in carbon export and its minimal elevation change of <100m over 1600km^2 (Smith et al. 2020). Over 30 years, a camera mounted on a tripod has taken a photo roughly every hour with strobes to illuminate the seafloor (Fig 1). Strobes only illuminate the area during image capture; at all other times there was no light input into the ecosystem which might attract fauna.

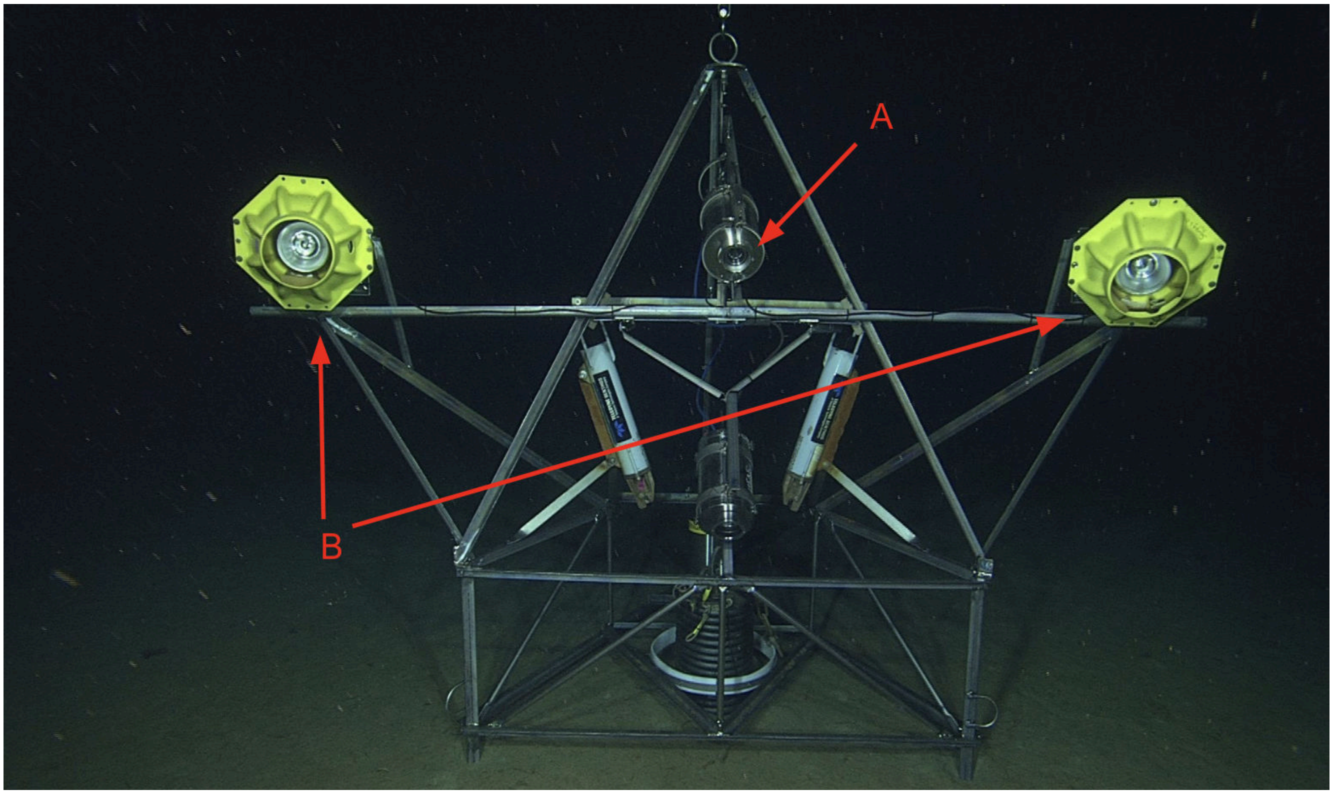

Fig.1: Time series camera mounted on tripod at Station M, an abyssal site off the coast of Central California. A) full frame camera responsible for photos used during this study, B) strobes used to illuminate the seafloor during photo capture.

In order to test the hypothesis that increased carbon input and thus increased sea cucumber density lead to a shorter aggregate residency time due to degradation method, an array of data would need to be collected. Overall residency time, whether the ultimate degradation occurred by consumption or other form, and what was happening in the environment at the sampling time.

Image Degradation Analysis

Of the 30 years of photos, three pulse events that are indicative of high carbon export to the deep ocean were selected to annotate and analyze. These events occurred in 2007, 2014, and 2017. These three were chosen due to their visible aggregate accumulations. Sections of frames that contained detrital aggregates were noted and of these frames, 20 were randomly selected for each pulse event. A random coordinate in the bottom half of each of the sixty images was selected and the aggregate closest to the marked coordinate was chosen for annotation. Each of the selected aggregates was monitored through the series of images and three different things were marked; the time the aggregate landed on the seafloor, the time the aggregate completely disappeared, and anytime an animal interacted with it. From these data points the total residency time of each aggregate was calculated, and further analysis of the final few frames for each aggregate was conducted to determine if the aggregate was consumed by megafauna. Due to the limitations of still imaging it was concluded that the aggregate was consumed if there was a megafauna pictured on top of the aggregate and the aggregate shrunk in size until it disappeared before the megafauna moved elsewhere.

. Image and Aggregate Hue Analysis

In some cases within the three deployment periods, insufficient background data existed to be able to determine the amount of carbon that had been deposited. To address this, a series of color analyses were run to elucidate how much carbon was entering the system. By comparing the hue of the bottom third of each image with the average hue of an aggregate, it was possible to determine how much of the floor was covered with aggregates. First, the green channel (RGB) was extracted from the bottom third of each image to calculate the average greenness of each image throughout the pulse event. Next, the hue values were extracted from the bottom third. Hue in this context is considered the angle on an RGB color wheel where 0° = red, 60° = yellow, 120° = green. Finally, singular hue values were selected from the center of each annotated aggregate within the first frame that the aggregate appeared.

Statistical and Graphical Analysis

Comparison of aggregate residency between pulse events.

A Kruskal-Wallis test was performed to determine whether a difference was present between the aggregate residency times across the three different deployments. Further pairwise comparisons were then conducted to determine where those differences were present.

Ratios of aggregates being consumed megafaunally or microbially

Within pulses the number of aggregates consumed by megafauna were totalled and compared with the number of aggregates that had degraded in other fashions. The percentages of each were calculated and compared within and across pulse groups. A Mann-Whitney U test was performed to distinguish whether there was a difference in residence times between fate of aggregates (i.e. if they were megafaunally consumed or degraded by other methods).

Average hue values

The average hue was plotted for each of the pulses as a time series; outliers were inspected and removed when necessary (due to fish blocking the frame or pictures being taken at the surface during deployment). The average aggregate hue was then calculated for each pulse and plotted as a horizontal bar.

RESULTS

There was a significant difference in aggregate residency time across pulses ($p<0.001$, $\chi^2 = 25.3$), a Pairwise Wilcoxon Rank-Sum Test showed that the three pulse events were distinct from one another ($p<0.001$)(Fig.2).

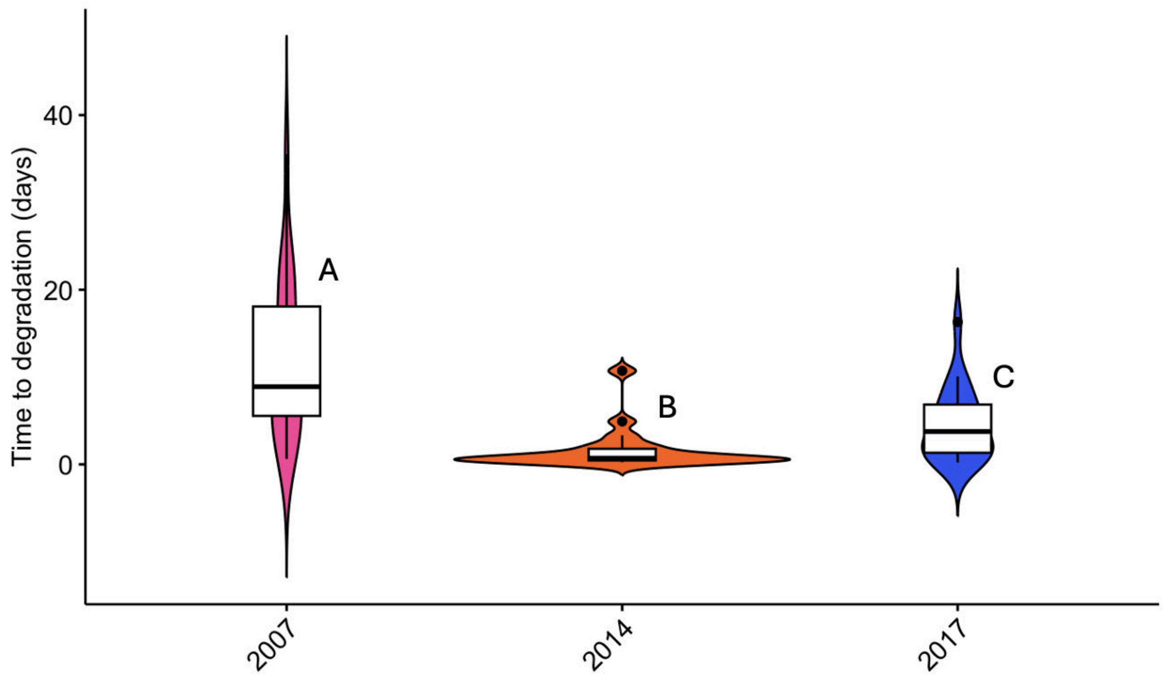

Fig.2: Violin plot showing the distribution of aggregate residence time across three camera deployments, labeled by year. Results from pairwise wilcoxon rank-sum test displayed by letter next to each plot. Width of each violin is representative of the density of data within that range of days, the black bar in the center of each represents the median and the white box represents the interquartile range for each deployment.

The dominant degradation pathway varied between pulses. All three pulses appear to have a different ratio of aggregates consumed megafaunally versus aggregates degraded in another fashion (Fig.3). The residence time of aggregates that were ultimately consumed was significantly shorter than that of those degraded in other ways ($p = 0.003$, $W = 248$)(Fig.4). The percentage of aggregates eaten by megafauna appears to correlate to total sea cucumber density in the corresponding year (Fig.5). The residency time of aggregates appears to inversely correlate to sea cucumber density in the corresponding year (Fig.5). The average greenness of the images showed no significant information about aggregate presence within the time series images. Hue values of the bottom third of each image differed between years with 2014 having the highest hue values across the entire time frame (Fig.6). 2014 hue values also tended closer to the average aggregate hue value of that year when compared to the other two years (Fig.6). 2007 had a clearer visual peak than the other two years which appeared to be consistent with hue values across the time period of the deployment.

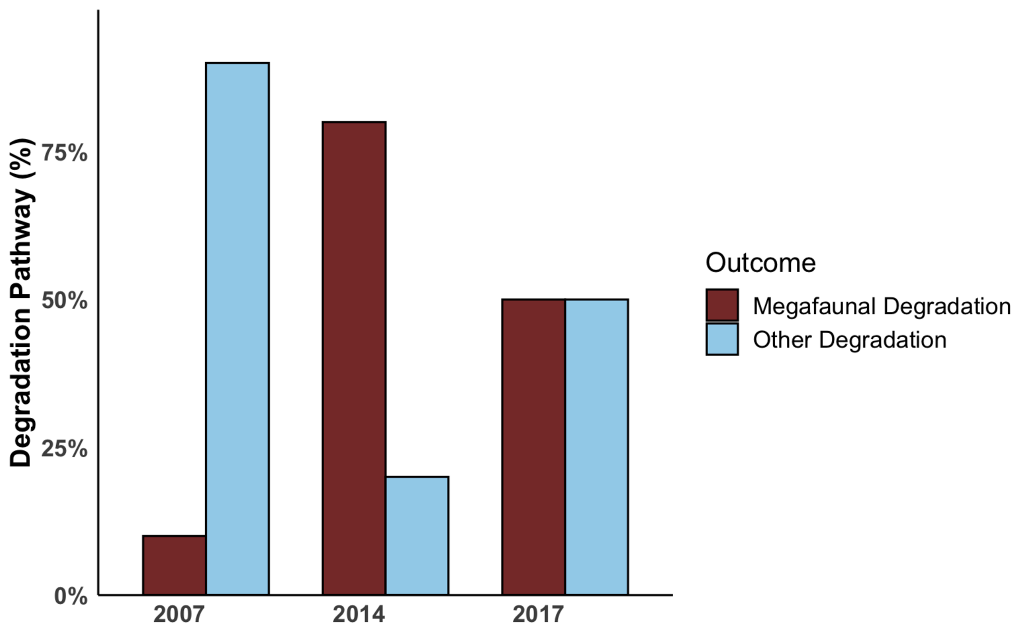

Fig.3: Bar chart showing the percentage of aggregates per deployment that degraded according to the different pathways. Deployments are labeled according to their year.

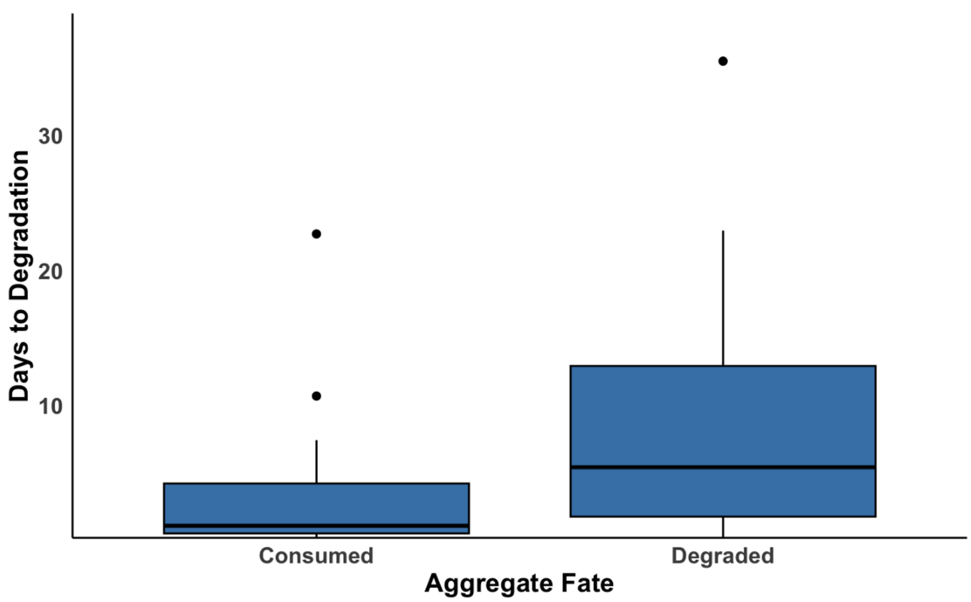

Fig.4: Box and whisker plot showing the distribution of degradation time according to aggregate fate. Outliers are represented by black dots and median values are shown as a black solid line.

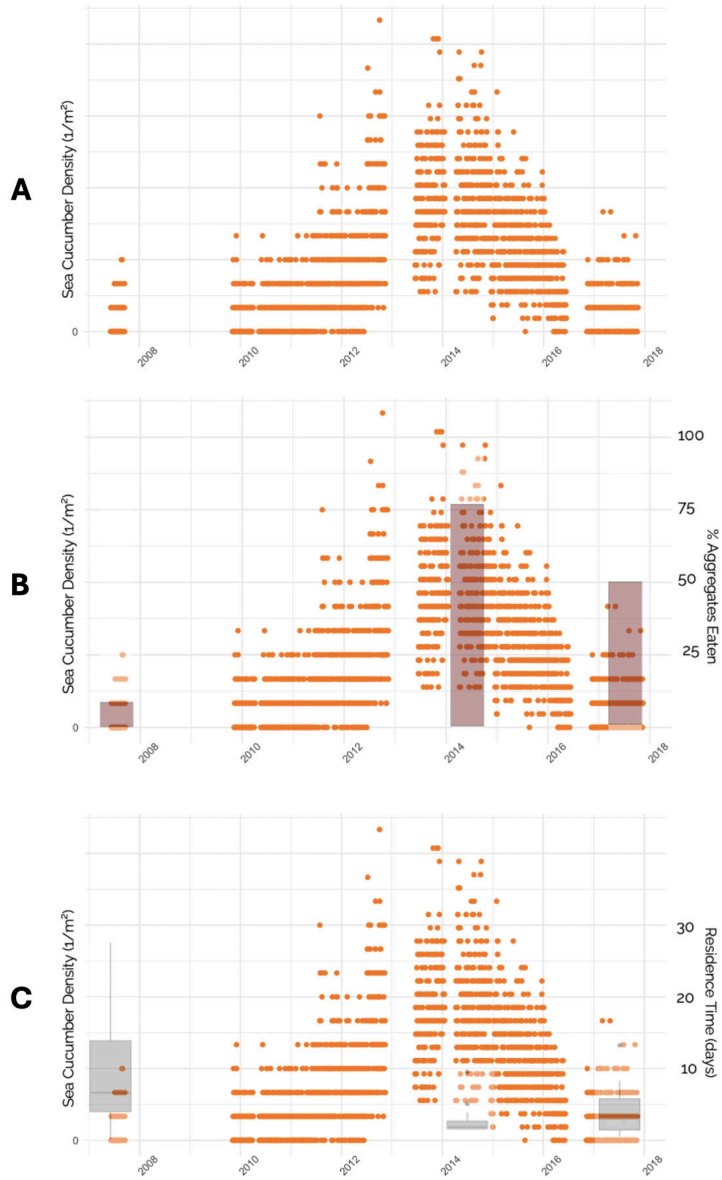

Fig.5: (A) Scatter plot showing sea cucumber density from 2007-2017 (Lemon et al. 2022). (B) Percentage of aggregates consumed by megafauna overlaid on the scatterplot of sea cucumber densities. (C) Box and whiskers of aggregate residence time overlaid on the scatterplot of sea cucumber density.

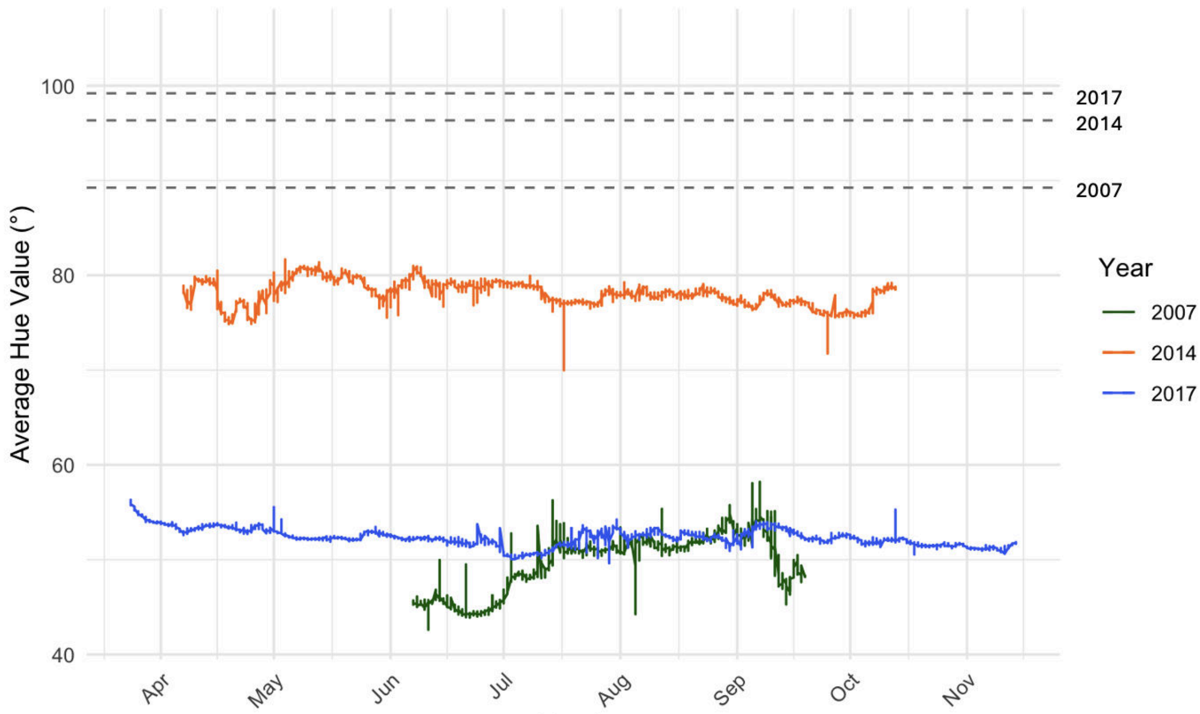

Fig.6: Average hue (°) as a time series extracted from the bottom third of each image shown by colored lines corresponding to their deployment year. Three horizontal dotted lines represent the average aggregate hue of each year as labeled.

DISCUSSION

Aggregates differed according to residency time which is unexpected given that all three deployments were indicative of high carbon flux. 2007 showed the highest variability across residency times, with an overall higher mean residence time than the other two camera deployments. Samples from 2014 had much lower variability, with most of the aggregates annotated having a relatively short residence time. 2017 had more variability than 2014 but less than 2007, and a mean residence time for aggregates that was in between the other two years. A closer look into the dominant degradation method across all three deployments makes it clear that the residency time is likely directly linked to how the aggregates are ultimately degraded as hypothesized (Fig.3). In 2007 only a small portion of the aggregates annotated were degraded by megafauna and the majority were degraded in other ways. It follows that an aggregate being degraded microbially, physically, or chemically is likely to have a much longer residence time than an aggregate being megafaunally consumed due to the relative time of these processes (Fig.4). In 2014 the majority of the aggregates annotated were megafaunally consumed – only a small portion of the aggregates were degraded in another fashion. This outcome corresponds to the relatively short residence time compared to 2007; the process of megafaunal consumption is much less time consuming than microbial, physical, or chemical degradation. In 2017 exactly half of the aggregates annotated were consumed megafaunally and half were degraded otherwise. Again, this is reflected in the overall aggregate residence time (ART) in 2017 being generally longer than 2014's ART but shorter than 2007's ART. It becomes clear when looking at methods of degradation that this is directly linked to residency time and has possible implications for exactly how much carbon is being sequestered into the sediment and also how quickly that carbon is sequestered. This relationship is further exemplified when looking at the time it takes aggregates to degrade when consumed and the time it takes aggregates to degrade when degraded in another fashion (Fig.4).

2014 had the highest density of sea cucumbers in relation to the other two deployment years (Lemon et al. 2022). When the data of sea cucumber density is overlaid with the aggregate trends (Fig.5) the relationship between the two factors appears to be quite distinct, when more sea cucumbers are present, more aggregates are consumed megafaunally and the shorter the overall ART is. We can also see the trends of sea cucumbers in the years in between the three deployment periods, which gives us an idea of what the population was doing leading up to the deployment and what happened after.

Sea cucumber abundance is directly linked to food concentration (Lemon et al. 2022). Mean annual POC flux is high for both 2007 ($14.1 \text{ mg C} \cdot \text{m}-2 \cdot \text{d}-1$) and 2017 ($17.1 \text{ mg C} \cdot \text{m}-2 \cdot \text{d}-1$) but is missing for 2014 (Smith et al. 2018). Data are missing due to sediment trap malfunction, likely caused by clogging, which is often due to high carbon input. However a quantitative number cannot be assigned to the amount of carbon entering the system in 2014 with the data at hand. All three deployments are considered pulse events, meaning 2014 data is likely to contain high POC flux, similar to the other two deployments. However we are unable to conclude whether the mean annual POC flux for that specific year was significantly higher than in the other two years, as indicated by the high concentration of sea cucumbers present and the high percentage of annotated aggregates being consumed. This is a substantial hole in the data that needs to be addressed, due to the fact that we want to know if there is a direct link between carbon export and sequestration, if more carbon equates to more sea cucumbers, then there is a risk that an excess of carbon entering the deep sea ecosystem could lead to a less efficient sequestration, with some of the carbon being used up in respiration.

The lack of concrete data to tell us how much carbon was entering the system led us to look into analyzing the hue data. The time series analysis of the mean hue of the bottom third of each image, proved incredibly interesting. 2014 average hue was significantly higher than the other two time series depictions despite all the camera settings and angles being identical. 2007 and 2017 had similar values, however 2007 showed more of a peak than 2017 which appeared to remain more constant. 2014 was fairly constant. The aggregate hues were consistently higher than the average hue of the bottom third of the image. One idea is that as the composition of the ocean floor shifted towards being coated in aggregates the average hue value of that section of the image would tend toward that higher value. If this were the case the hue data would be indicative of 2014 having a much higher aggregate benthic composition than the other two years. This finding would be consistent with the fact that data was unable to be collected due to a clogging.

The mean hue values for aggregates across the three deployments were similar, however it was interesting to note how they increased by year. Hue in this context was not being used to measure a quality of the detrital material as we do not conclusively know what hue value would directly correspond to qualities within the material. The change in hue over the years though is interesting and something that future researchers could look into.

Further Work

The mean hue values for aggregates across the three deployments were similar, however it was interesting to note how they increased by year. Hue in this context was not being used to measure a quality of the detrital material as we do not conclusively know what hue value would directly correspond to qualities within the material. The change in hue over the years though is interesting and something that future researchers could look into.

During this study, the 20 aggregates that were annotated per deployment were also outlined within the VARS software. Due to time constraints the data was not used within the scope of this project however these outlines still exist within VARS and can be used to calculate the size of the aggregates according to the camera angle using the Canadian Grid Method (Wakefield & Genin 1987).

Further hue work in which a specific range of hues are extracted and averaged from the bottom third of the image, whilst excluding those hues that will not be present in the sediment (i.e. a reddish hue like that of a sea cucumber), could be a way that future scientists can polish the method of using hue as an indicator of detrital cover.

Fluorescence data could be used from the years when the rover fluorescence camera was used to determine whether chlorophyll a content within detritus on the seafloor has an effect on its residency time. The three years that were analyzed within this study did not all have that data available, rerunning a study similar to this one but choosing years where this data is available could yield some interesting results.

CONCLUSION

Aggregate residency time varied distinctly by camera deployment, seemingly in correlation with the sea cucumber abundance within that year. The quantitative amount of carbon entering the system was unable to be obtained due to lack of data, however when hue values within the image and from the aggregates themselves are used as an indicator of detrital cover, it appears that detrital cover also correlates with the aggregate residence time. Thus it is likely that when there is an increase of carbon rich material entering the system, and a related increase in megafauna such as sea cucumbers consuming the material, the ratio of carbon being sequestered into the sediment rather than dispersed or cycled in other fashions is effected, the extent to which we cannot conclude yet.

ACKNOWLEDGEMENTS

Thank you to my mentor Crissy Huffard for guiding me through this research project and offering assistance and feedback throughout the whole process. I would also like to thank George Matsumoto for making this internship possible, Lisa Parr for helping me to turn this research into a MOP project, and my fellow interns for keeping me motivated.

WORKS CITED

Durden JM, Bett BJ, Huffard CL, Pebody C, Ruhl HA, Smith KL (2020) Response of deep-sea deposit-feeders to detrital inputs: A comparison of two abyssal time-series sites. Deep Sea Research Part II: Topical Studies in Oceanography 173:104677

Gage JD, Tyler PA (1991) Deep-Sea Biology. Journal of the Marine Biological Association

Iversen MH (2023) Carbon export in the ocean: A biologist's perspective. Annual Review of Marine Science 15:357–381

Lauerman LML, Kaufmann RS, Smith KL (1996) Distribution and abundance of epibenthic megafauna at a long time-series station in the Abyssal Northeast Pacific. Deep Sea Research Part I: Oceanographic Research Papers 43:1075–1103

Lemon LM, Smith KL, Huffard CL (2022) Abyssal epibenthic holothurians respond differently to food quantity and concentration fluctuations over a decade of daily observation (2007–2017). Deep Sea Research Part I: Oceanographic Research Papers 188:103853

RAVEN JA, FALKOWSKI PG (1999) Oceanic sinks for Atmospheric Co2. Plant, Cell & Environment 22:741–755

Ruhl HA (2007) Abundance and size distribution dynamics of abyssal epibenthic megafauna in the Northeast Pacific. Ecology 88:1250–1262

Sabine CL, Feely RA, Millero FJ, Dickson AG, Langdon C, Mecking S, Greeley D (2008) Decadal changes in Pacific Carbon. Journal of Geophysical Research: Oceans 113

Smith KL, Baldwin RJ, Glatts RC, Kaufmann RS, Fisher EC (1998) Detrital aggregates on the sea floor: Chemical composition and aerobic decomposition rates at a time-series station in the abyssal NE Pacific. Deep Sea Research Part II: Topical Studies in Oceanography 45:843–880

Smith KL, Huffard CL, Ruhl HA (2020) Thirty-year time series study at a station in the abyssal NE Pacific: An introduction. Deep Sea Research Part II: Topical Studies in Oceanography 173:104764

Zhang Y, Zhao M, Cui Q, Fan W, Qi J, Chen Y, Zhang Y, Gao K, Fan J, Wang G, Yan C, Lu H, Luo Y, Zhang Z, Zheng Q, Xiao W, Jiao N (2017) Processes of coastal ecosystem carbon sequestration and approaches for increasing Carbon Sink. Science China Earth Sciences 60:809–820