# ASSESSING HUMAN-INDUCED CORAL REEF DISTURBANCES FROM VISITORS AT HANAUMA BAY NATURE PRESERVE

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I certify I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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*This thesis is dedicated to my loved ones for always believing in me and my dreams,*

*and to*

*GOD for courage, strength, and wisdom.*

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# ABSTRACT

It has been noted in many research papers that regions with high snorkeling and diving activity damages coral reef ecosystems. I investigated the effects of visitor snorkeling density, and the number of times snorkelers physically disturbed the reef. Four plots were designated for bimonthly monitoring, where the number of snorkelers entering each plot and their interaction with the reef was recorded. Coral health was qualitatively observed, and the surface area of the coral tissue was quantitatively measured. My results show a direct relationship between snorkeling density and the number of disturbances. However, there is no evidence of visitor density and coral health impairment. There was no coral breakage or abrasions from snorkelers during the data collection period, possibly a result of low coral cover across the bay, limited branching morphology, and/or species with high skeletal strength due to historical disturbances from higher water motion and extensive visitors. Corals in each of the plots experienced tissue loss mainly from preexisting lesions or tissue damage; the causation of the previous coral injury is unknown. Future management actions in Hanauma Bay could limit the number of visitors and occurrence of reef disturbances to potentially reduce tissue loss and promote coral recruitment.

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# 1.0 INTRODUCTION

## 1.1 Study Location

Hanauma Bay is a 101-acre nature preserve located in East Honolulu, Oʻahu, Hawaiʻi. It has a history of recreational usage by Hawaiian nobility dating back to the 1800s (Hoover, 2001). In 1928, Hanauma Bay was purchased from the estate of Bernice Pauahi Bishop by the City and County of Honolulu and became available for public use (Hoover, 2001). The bay was deemed a Marine Life Conservation District (MLCD) in 1967, prohibiting fishing and taking of marine life, shells, rocks, and sand (City and County of Honolulu Department of Parks and Recreation). It is an important area of study as it is the most popular snorkeling location on Oʻahu, with an average of 3,300 daily visitors prior to the COVID-19 outbreak. However, high visitor occupancy to the bay may impair the health of aquatic organisms, including coral reefs.

## 1.2 Coral Reef Significance

Corals are holobiont, composed of tiny living plant cells called zooxanthellae, fungi, and a rich microbiome (Rowan, 1998). Corals support a variety of marine life through food, shelter, and nutrients, making them the foundation of coastal ecosystems in the tropics (Muscatine et al., 1981). Coral reefs face many stressors, mainly from global climate processes that are hard to manage, such as warming ocean temperatures, ocean acidification, and sea level rise (Ban et al., 2014; Fabricius, 2008; Kuffner, 2018). Some local stressors include pollutants from sewage discharge, excess nutrients, marine plastics, fishing pressure, coastal construction, chemical sunscreens, and physical contact with the reef (Reopanichkul et al., 2009; Danovaro et al., 2008; Stender et al., 2014; Lamb et al., 2018). Therefore, it is key to mitigate regional-scale disturbances to reefs that are under human control.

### 1.3 Local Coral Reef Disturbances

The purpose of this paper is to discuss one threat to coral reefs, which is physical damage caused by ocean users. Hanauma Bay is a unique location to design this type of study, with its very shallow reef system accessible to visitors and a deeper reef offshore. Even at high tides, the depth of the inner reef is less than one meter (pers. obs.), making these coral reefs particularly vulnerable to physical contact by snorkelers. Snorkelers contact the reef by kicking, stepping, sitting, grabbing, and/or body scraping. This can result in lesions, broken branches, or indentations to the tissue layer and damage can extend to the calcium carbonate structure (Giglio et al., 2016; Leujak and Ormond, 2008; Harriott et al., 1997). Even with caution, it is probable that a snorkeler will contact the reef in the shallow environment of Hanauma Bay. Physical contact or indirect contact through sediment suspension and deposition can damage corals (Giglio et al., 2016; Rouphael and Inglis, 1997). When sediments smother the tissue layer, coral polyps can experience a reduction in growth and reproduction (Webler and Jakubowski, 2016; Hawkins and Roberts, 1994; Neil, 1990). Additionally, human contact can abrade the thin protective tissue layer on the surface of the coral, allowing algae to colonize the surface (Webler and Jakubowski, 2016). The accumulation of natural and anthropogenic stressors are disturbances to the reef that can impair long-term growth and survival (Poonian et al., 2010).

Natural reef disturbances also occur from fish predation, burrowing organisms, and competition with other coral species. Parrotfishes are major contributors to sand production via consumption of coral tissue (Frydl and Stearn, 1978). Corallivore bites are identifiable based on the size and shape of the lesion. Generally, a fish bite is a uniform circle, only a few centimeters in diameter, sometimes exposing a greenish tone in the center of the lesion from filamentous algae tissue (Rotjan and Lewis, 2008; pers. obs.). A burrowing organism indents a fissure, mainly at the base of coral branches from chemical means to excavate the coral (Eyes of the Reef Hawai‘i). *Hapalocarcinus* or *Pseudohaplocarcinus* (commonly known as Gall crabs or Kahe crabs) inhabit the base of coral branches and may pinch some of the coral polyps and carbonate skeleton. This is detectable from two proximal indentations from the pincher (Eyes of the Reef Hawai‘i). There are many biological interactions with the reef, but predation may be selective based on coral morphology and species (Rotjan and Lewis, 2005), making smoother lobe corals more appealing than the jagged skeleton of *Pocillopora meandrina*.

### 1.4 Goals of the Study

The global COVID-19 pandemic limited tourism and closed Hanauma Bay in March of 2020. This was a unique opportunity for the wildlife in the bay to experience a 9-month period without any human contact, except for occasional researchers. Numerous studies took place to examine the potential recovery effects during the closure. Although the duration of the Hanauma Bay closure was a minimal period compared to the lifespan and growth of corals, the 9-month closure presented an opportunity to survey “baseline” coral health from March 2020 to the limited reopening date in December 2020. Upon reopening to the public, the goal of this research was to quantify the number of snorkelers entering specific sectors of the reef and record the type of physical reef disturbance occurring. Moreover, corals were monitored in those sections and their overall condition was observed from December 2020 to September 2021. I hypothesized that the regions of high visitor activity in the inner shallow reef would have the highest reef disturbance rates, resulting in coral damage or lesions from physical contact as compared to coral conditions prior to the reopening of Hanauma Bay.

# 2.0 METHODS

## 2.1 Location Descriptions in Hanauma Bay

Hanauma Bay is divided between four sectors spanning from East to West: Backdoor Lagoon, Keyhole Lagoon, Sandman's Patch, and Witches Brew (fig. 1).

**Figure 1. Hanauma Bay Nature Preserve. Study region is on the East side of the bay. Basemap: Google Earth (https://earth.google.com/web).**

An artificial reef of large basalt boulders, called the "algal reef" separates the inside fringing reef and outside reef approximately 100 meters from shore (Hoover, 2001). To reach the outside, snorkelers must swim through a strong current system represented by two channel markers on the East and West side of the bay. Therefore, most snorkelers, especially tourists, remain in the inshore reef. Data was collected on the East side of the bay, particularly in Backdoor and Keyhole Lagoon. Station selection criteria included level of snorkelers, substrate similarity, depth, spatial complexity, and distance from shore. Selected stations are where most snorkelers enter and exit the water due to sandy entry points. The West side of Hanauma Bay has more variable coral species and rock/reef formations and were not included in the research.

### 2.2 Coral Species of Study

Corals were examined in five sections on the East side of Hanauma Bay. Only one common coral species *Pocillopora meandrina* (Cauliflower Coral) was used in the research because it is one of the only remaining coral species residing in the bay, except for *Porites Lobata* on the West end, and an extremely small population of *Pocillopora damicornis* and *Montipora capitata* on the East end (pers. obs.). Compared to three other species present around Hawaiʻi, *P. meandrina* has the strongest skeletal structure, which is a response to hydraulic stress (Rodgers et al., 2003). Cauliflower coral spends more time and energy developing a hard skeletal structure, becoming more resistant to waves and turbulence rather than to growth. This is a response to resiliency in surviving in high wave energy environments.

### 2.3 Data Collection

Surveys were conducted bimonthly from the reopening of Hanauma Bay in December 2020 to September 2021. A total of five plots, each 5 x 5 meters in length and marked by tie-wraps, were designated in three locations across the East side of the bay (two plots in Backdoor Lagoon, two plots in Keyhole Lagoon, and one plot outside the main reef break (fig. 2). The singular plot was only surveyed once and is discussed below in more detail in section 2.4. The other four plots were surveyed bimonthly during the 9-month data collection period. Each plot was surveyed in 30-minute intervals from 11:00 am to 1:00 pm. The survey order and thus survey time of each plot rotated to allow for possible temporal differences in data sampling.

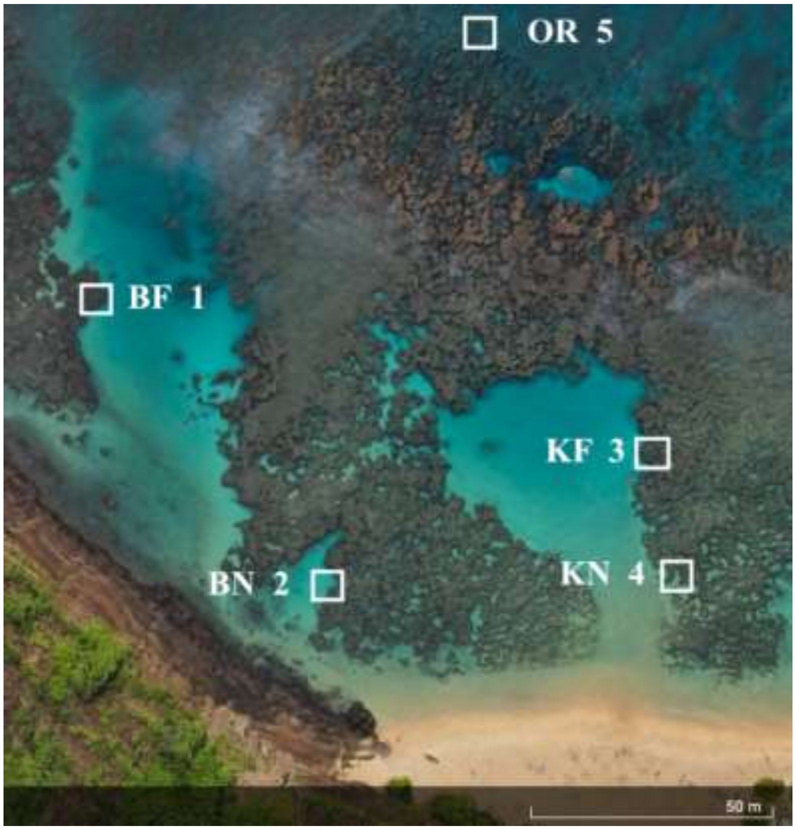

**Figure 2. Designated plots for data collection in Hanauma Bay: Backdoor far-shore plot (BF, 1), Backdoor near-shore plot (BN, 2), Keyhole far-shore plot (KF, 3), and Keyhole near-shore plot (KN, 4), outside-reef plot (OR, 5). The image is to scale, but the white boxes are not. Basemap: Google Earth (https://earth.google.com/web).**

### 2.4 Plot Methodological Details

Of the four plots on the inside reef, two of the near-shore plots were approximately 28 meters from shore and the two far-shore plots were 50 meters from shore. This survey design compared plots closer to shore to the plots further from shore. For simplicity, each of the plots was abbreviated with a corresponding number: Backdoor far-shore plot (BF, 1), Backdoor near-shore plot (BN, 2), Keyhole far-shore plot (KF, 3), and Keyhole near-shore plot (KN, 4). A fifth plot referred to as the outside reef plot (OR, 5) was surveyed once to document corals that are rarely in contact with snorkelers as a comparison to the inner reef plots. Plot 5 is a difficult sector to survey due to high surf, currents, and poor visibility through the channel. The corals residing at this location are below a depth of human reach (< 2 meters), serving as an observatory reference to subtract any biological reef disturbances from anthropogenic disturbances found in inner reef plots.

### 2.5 Counting Snorkelers and Reef Disturbances

Prior to surveying, observations of ocean conditions, including tides, weather, and swell were noted. Snorkelers were counted once they entered the plot. The behavior of each snorkeler was recorded and the number of times they touched the reef was counted. The type of reef disturbance was categorized as kicking, stepping, sitting, grabbing, or body grazing the reef. Each individual physical contact to the substratum (i.e., bare, macroalgae-covered, and crustose coralline algae-covered) and to the living and dead corals was tallied. Data was recorded on a slate with water-proof paper and snorkelers were observed underwater from 2 to 3 meters away.

### 2.6 Coral Health Documentation and Images

Following data collection at each plot, photos of *Pocillopora meandrina* were taken inside or near the plot borders. Plots 1 and 4 had seven corals, plot 3 had one coral, and plot 2 had no corals, totaling fifteen corals monitored on the inside reef during the research. Ideally, each plot would have seven or more corals to document overall health and disturbances. However, the inside locations across the Hanauma Bay have a small percentage of living coral and many are overgrown with algae or covered in sediment. An additional seven corals were viewed on the outer reef, totaling twenty-two corals for the entire research project. A total of 18 photos of each coral over the 9-month period were collected for the inside plots. A Master lock© lock combination was placed next to the coral inside the image as a reference scale to calculate coral surface area. Each of the 15 corals was assigned a number that was represented in the photos by changing the lock combination dials. Additionally, qualitative observations of changes in coral tissue or structure were noted, including new lesions, abrasions, or discoloration of tissue.

### 2.7 Natural Versus Anthropogenic Disturbances

Identifying reef interactions was important to determine new or existing damage to coral. Each coral was qualitatively analyzed for biological disturbances based on the description in section 1.3. The total number of bite marks or burrows to each coral colony were not counted or measured. The natural disturbances were only used to compare damage inflicted by humans or other organisms, which is a significant aspect of the research. Without the distinction of natural and anthropogenic reef contacts, the effects of snorkelers on the reef would be unidentifiable.

### 2.8 Data Analysis and Software

For data analysis, ImageJ, an open-source software by Schindelin et al. (2015) was used to calculate the surface area of the coral from top-view images. Size reference was derived from the lock placed in each photo. Each dial on the lock is 0.7 cm in length. The total surface area was computed three times for each image and averaged to reduce variability. Bite marks and other biologically induced lesions to the coral tissue were included in the surface area if the tissue was presumably alive. Dead or algae-covered tissue was excluded from the total living tissue surface area. Surface area measurements were repeated for every survey.

## 3.0 RESULTS

### 3.1 The Number of Snorkelers and Reef Disturbances

A total of 327 snorkelers were observed in all the plots combined, with the highest visitation in KN (n= 144). The lowest snorkeler count was in BF (n= 23) and BN and KF had intermediate values (n= 67, n= 93), respectively. Over the study period, 168 reef disturbances were documented, < 5 of the disturbances were directly to coral heads and the rest of the disturbances were to the other substratum. Most disturbances occurred in KN (n= 65) followed closely by KF (n= 61) (table 1). Grabbing was the most common category of reef disturbance and was three times higher than the other categories. The second highest reef disturbance was standing (fig. 3).

In the 30-minute survey period, KN experienced the highest snorkeling density and reef contacts (fig. 4). However, the proportion of snorkelers to reef disturbances was highest for KF (66%) followed by BF (61%) making the relative frequency of reef contacts to snorkelers swimming through the plot highest for KF and BF. Although BF had the lowest visitation rate, more than half the snorkelers entering the plot contributed to a reef disturbance (table 1).

**Table 1. Comparison of the number of visitors separated by plot and corresponding reef disturbance categories. FD = frequency of disturbance, is separated by plot and reef disturbance category. The percentage of visitor contact by plot was calculated from the total frequency of disturbance divided by the total number of visitors.**

| Plot | Number of Visitors | Stand | Sit | Kick | Grab | Body Graze | FD by plot | Visitor Contact Percent (%) |
|---|---|---|---|---|---|---|---|---|
| BF (1) | 23 | 0 | 0 | 2 | 10 | 2 | 14 | 60.87 |
| BN (2) | 67 | 4 | 3 | 2 | 17 | 2 | 28 | 41.79 |
| KF (3) | 93 | 12 | 5 | 8 | 28 | 8 | 61 | 65.59 |
| KN (4) | 144 | 11 | 7 | 11 | 31 | 5 | 65 | 45.14 |
| FD by category | 327 | 27 | 15 | 23 | 86 | 17 | | |

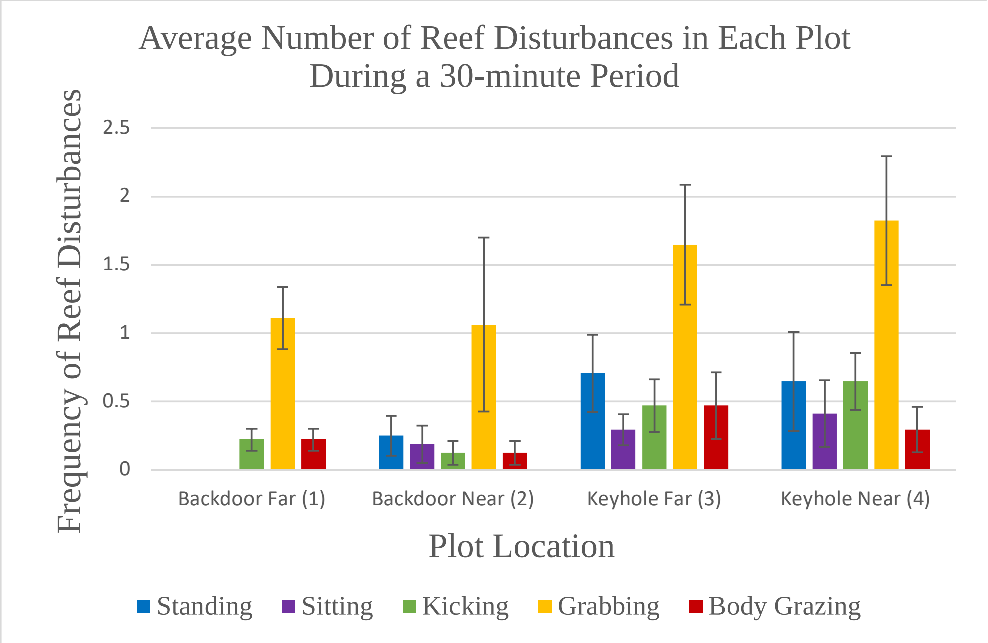

**Figure 3. Frequency of reef disturbances averaged over a 30-minute survey period categorized by reef disturbance and plot location. Standard error is included.**

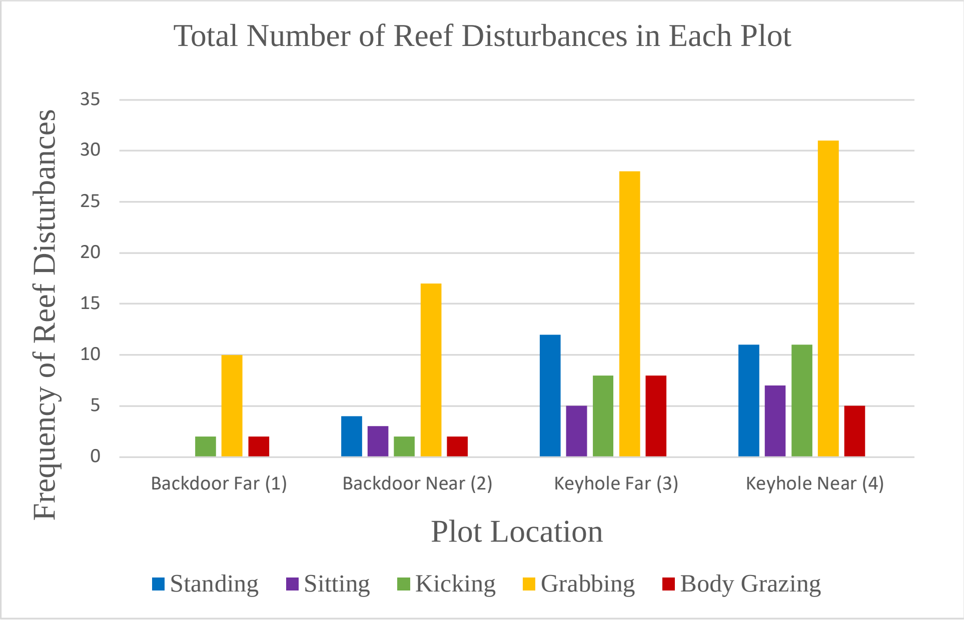

**Figure 4. Total frequency of reef disturbances over entire data collection period categorized by reef disturbance and plot location.**

3.2 Coral Health Documentation and Images

From the initial survey before Hanauma Bay was reopened to the public, corals were observed to identify preexisting dead branches and pink tissue regions, which are indicators of stress. Prevalent dead branches were recorded on corals A, D, E, F, H, I, N, and O (see Appendix for coral photos).

Throughout the survey period, most corals either lost tissue surface area or remained unchanged (table 2). The one exception is coral M that increased in tissue surface area based on ImageJ measurements (fig 7). 12 of the 42 data points are unavailable due to photographic error (table 2). The tide difference and slight misplacement of the lock in the images distorted the scale.

Some specific examples of tissue loss are found from coral J and K. Coral J was bleached on May 30th, 2021, resulting in major tissue loss on the top of the coral head (fig. 5). Coral K developed tiny algal specks first noticed on April 4th, 2021. As time progressed, more tiny algae settled on the coral head. By the final survey, a colony of algae was noticeable (Appendix fig. A.12).

**Figure 5. (Left): Coral J bleached between May 16th (Survey #9) and May 30th (Survey #10). Only the top portion of the coral experienced discoloration. (Right): Coral J revisited on June 13th (Survey #11), two weeks following the initial assessment. Turf algae settlement was observed succeeding tissue mortality.**

**Table 2. Determining the change in living coral tissue surface area from the first survey on December 4, 2020 (Survey #0) and the last survey on September 26, 2021 (Survey #17) in cm$^2$. Δ SA = the change in surface area. A positive change in surface area indicates coral growth and a negative change in surface area indicates tissue loss. Some values are not applicable due to photographic error. Standard error (SE) values are in cm$^2$.**

| Coral Identification | Coral Reference Letter | Survey #0 SA [cm$^2$] ± SE | Survey #17 SA [cm$^2$] ± SE | Δ SA [cm$^2$] ± SE |
|---|---|---|---|---|
| BF1001 | A | 283.209 ± 16.29 | 234.014 ± 3.56 | -49.195 ± 16.67 |
| BF1002 | B | 655.709 ± 12.08 | 586.255 ± 15.57 | -69.454 ± 19.71 |
| BF1003 | C | 1303.139 ± 7.71 | 1219.844 ± 5.76 | -83.295 ± 9.62 |
| BF1004 | D | N/A | N/A | N/A |
| BF1005 | E | 927.345 ± 38.34 | 928.630 ± 4.55 | 1.285 ± 21.12 |
| BF1006 | F | 352.079 ± 20.15 | 324.527 ± 4.70 | -27.553 ± 20.66 |
| BF1007 | G | N/A | N/A | N/A |
| KF3001 | H | 216.760 ± 4.35 | 218.909 ± 2.19 | 2.148 ± 6.40 |
| KF3002 | I | 213.809 ± 16.46 | 138.295 ± 4.69 | -75.514 ± 16.60 |
| KF3003 | J | N/A | N/A | N/A |
| KF3004 | K | N/A | N/A | N/A |
| KF3005 | L | N/A | N/A | N/A |
| KF3006 | M | 525.572 ± 19.46 | 587.979 ± 4.69 | 62.407 ± 20.01 |
| KF3007 | N | 156.024 ± 4.66 | 153.81 ± 3.66 | -2.214 ± 5.92 |
| KN4001 | O | 281.318 ± 8.11 | 268.492 ± 0.31 | -12.826 ± 8.11 |

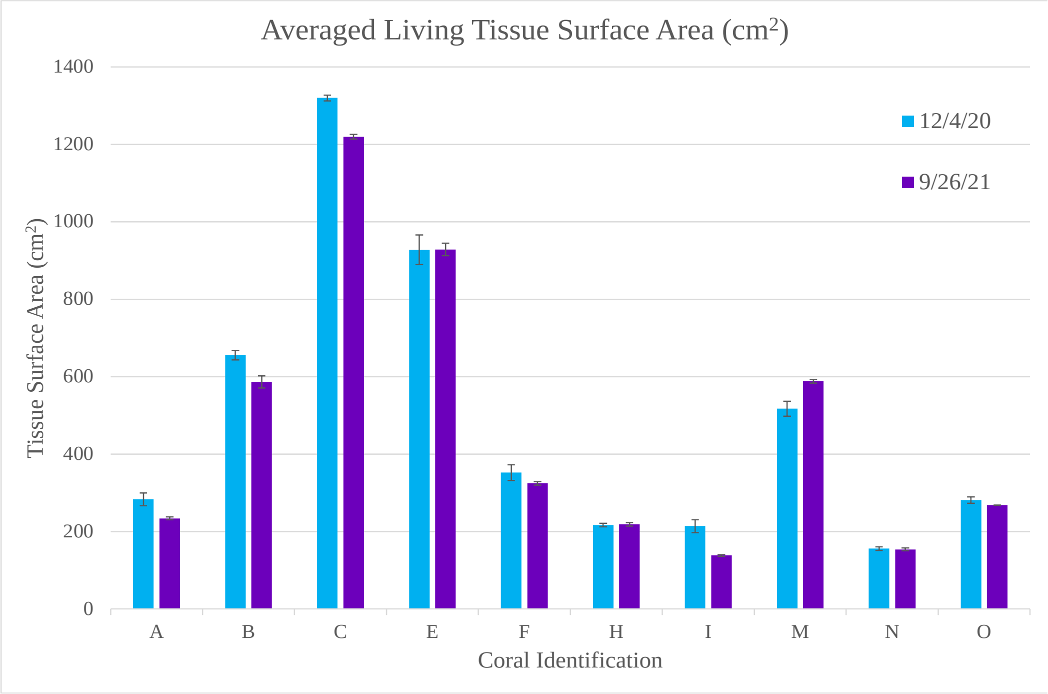

**Figure 6. Averaged living tissue surface area (cm$^2$) from the first survey on 12/04/20 (Survey #0) compared to the last survey on 09/26/21 (Survey #17). Standard error bars are in cm$^2$.**

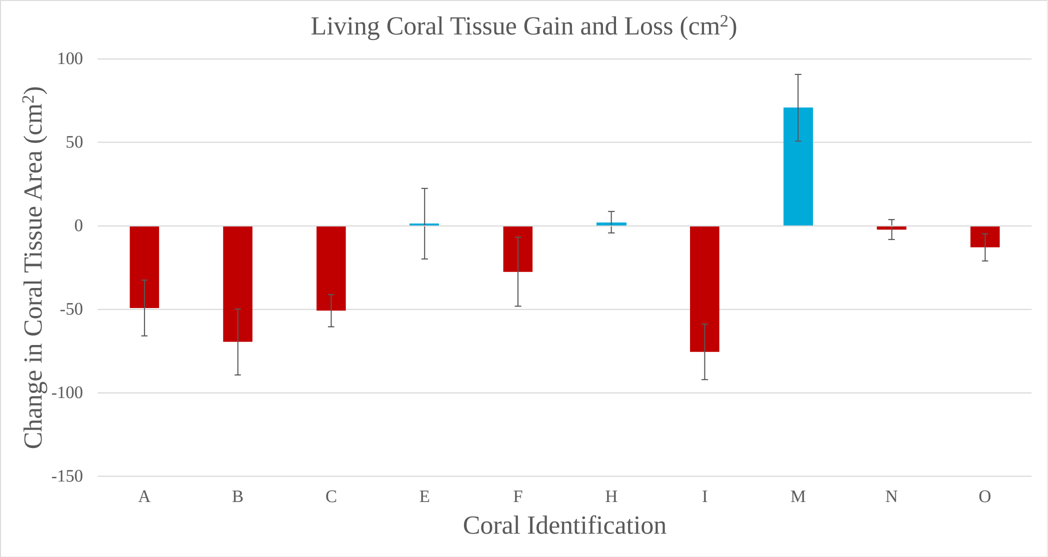

**Figure 7. The change in tissue surface area (cm$^2$) from the first survey on 12/04/20 (Survey #0) compared to the last survey on 09/26/21 (Survey #17). The blue bars indicate tissue growth, and the red bars indicate tissue loss. Standard error bars are in cm$^2$.**

## 3.3 Natural vs. Anthropogenic Disturbances

Biological disturbances were detected in the initial survey. All coral colonies surveyed had noticeable fish bites except corals F, G, L, and O. Coral I had dead tissue below the branch tips most likely from a burrowing organism (see Appendix for images). As data collection progressed, there were no obvious abrasions, broken branches, or lesions caused by snorkelers. It is possible that more snorkelers touched the surveyed corals, but the contact did not result in any noticeable injury.

In comparison to the outer reef (OR), corals in OR experienced the same biological disturbances of fish bites, turf algae, and sediment-covered branches. The abiotic stressors occurring in the inside reef of Hanauma Bay apply to the outside reef as well.

## 4.0 DISCUSSION

### 4.1 The Number of Snorkelers and Reef Disturbances

The total number of visitors and reef disturbances was highest for KN followed by KF, BN, and BF. A total of 327 snorkelers contributed to 168 reef disturbances in the 9-month survey period, which equates to a ratio of approximately one disturbance for every two snorkelers. Less than 3% of the disturbances were directly to a coral colony and the rest of the contact was to the substratum (bare reef, macroalgae, or crustose coralline algae). It is plausible that snorkelers noticed me with a clipboard underwater and altered their behavior to be more cautious with directly touching the corals. The results of high disturbance to the reef does not show much of an effect because most of the substratum is rock, algae covered sediment, or crustose coralline algae. Since most of the reef appears "dead", identifying the effects from physical contact to the substratum is limited.

The high visitation and reef disturbance rate occurred in KN because most people enter and exit the water at this location. A similar pattern of high trampling near water-entry points in popular tourist destinations was found in the Red Sea reef flats (Leujak and Ormond, 2008). KN is located next to a large sand patch where many snorkelers put on their equipment. For some, it is their first time using a mask and fins. As the visitors are comfortable wearing their gear, they swim over to the close reef sections nearshore where the KN plot is located.

The far shore plots of Backdoor and Keyhole Lagoon had the highest disturbance to visitor proportion. This may be the result of higher wave action and turbidity closer to the fringing reef. Snorkelers may be more likely to grab onto the reef in stronger ocean conditions, regardless of snorkeling experience.

Grabbing was the most common reef disturbance and was documented three times as often as the other categories of physical contact. Based on observations, grabbing was a method for snorkelers to move over the reef without scraping their knees or legs from kicking, especially during low tide. The second highest disturbance was standing on the reef. Standing was mainly intentional as a method for snorkelers to locate each other if separated. Other disturbances included kicking, which occurred mostly during low tide since the fins add additional length to the snorkeler's legs. Body grazing was observed when snorkelers moved across an extremely shallow reef shelf and their entire body was submerged on top of the reef. Another observed behavior of snorkelers was sitting on the reef, especially with high winds and swell. The water motion would toss snorkelers putting them in a sitting position on the reef. This may be an effect of inexperienced snorkeling.

An additional category of reef disturbance found in the literature is sedimentation via resuspending sand as snorkelers kick (Leujak and Ormond, 2008; Giglio et al., 2016; Harriot et al., 1997; Rouphael and Inglis, 1997; Luna et al., 2009). Sedimentation was not included in data collection because the plots were only located over reef substrate. There is a possibility that some corals on the edge of the reef shelf, including A and H, are subject to higher sedimentation rates due to snorkelers kicking sand. Since both of those corals were found with sediment-covered dead branches from the time of the initial survey, the resulting effects of increased sedimentation after reopening of the bay could not be determined. The reef disturbance of increased sediment load smothers the tissue layer and reduces coral growth and reproduction (Hawkins and Roberts, 1994; Neil, 1990; Webler and Jakubowski, 2016). Additionally, the high sedimentation across Hanauma Bay can limit coral recruits for future colony growth. Sediment resuspension in Hanauma Bay can be correlated to visitor density and snorkeling activity because the mean clarity was 5.9 meters clearer during COVID-19 closures than on the public days (Severino et al., 2020).

## 4.2 Coral Health Documentation and Images

Most corals from the initial survey had dead branches, discoloration of tissue, and algal growth. The cause of the preliminary damage is unknown due to a lack of historical photo documentation. In general, tissue loss progresses from a tissue lesion, followed by macroalgae settlement then, algae mortality, and sedimentation deposition. This specific progress was observed with coral C during the 4th survey in February. One branch tip bleached to a light grey color without evidence of any physical damage. The branch continued to decline with subsequent surrounding coral branches following. The lack of noticeable damage leaves the cause of tissue loss unknown, suggesting potential internal injuries or damage from burrowing organisms or pathogens (Rodríguez-Villalobos et al., 2015). In other words, a single coral branch bleached and the section below the branch also became covered in sediment, therefore, it could have been targeted by another organism. Tissue loss for *Pocillopora meandrina* has been documented previously in Hanauma Bay. Some of the tissue degeneration is by *Drupella cornus* (corallivorous snail) but the other instances have unknown sources (Walton, 2003 Dissertation).

The bright pink portions of some coral branches indicate coral stress (Bongiorni and Rinkevich, 2005). Researchers believe the pink coloration is from a loss of coral tissue and zooxanthellae, or it is from pathogens inducing the pigmentation (D’Angelo et al., 2012). During a stress event, the zooxanthellae are removed from the coral polyps and the tissue is no longer pigmented by the *Symbiodinium* spp. dinoflagellates (Jones et al., 1998; Curran and Bernard, 2021). Instead, chromoproteins, non-fluorescent photopigments in the tissues, show through the tissue now devoid of symbionts (Donà, 2019 Dissertation). The chromoproteins may be used as photoprotection for the zooxanthellae in high light environments (D’Angelo et al., 2012).

Other researchers link the pink pigmentation to coral diseases such as pink-line syndrome (D’Angelo et al., 2012). Pink-line syndrome is a disease that appears pink between living and dead tissue, induced by fungi and a cyanobacterium, *Phormidium valderianum* (Ravindran and Raghukumar, 2006). The process of pink-like syndrome infiltration proposed by Ravindran and Raghukumar (2006), beings with cyanobacterium settlement on the coral host. *P. valderianum* increase carbon dioxide concentrations around the coral polyps by respiration, causing the zooxanthellae to escalate photosynthesis production. The photosynthate is utilized by the zooxanthellae to grow, rather than diverting the sugars to the coral host. In return, the coral loses its portion of photosynthate, which hinders growth and calcification. The weakened coral host, acidic environment, and higher carbon dioxide concentrations degenerate the coensacral tissue, turning the polyp tissue pink (Ravindran and Raghukumar, 2006).

The pink pigmentation on *P. meandrina* is potentially a symptom of stress from environmental and biological factors through the expression of chromoproteins (Bongiorni and Rinkevich, 2005), or it is the product of disease (Ravindran et al., 2015). In either case, the pink patches found on numerous corals surveyed in Hanauma Bay such as A, D, H, M and O are likely to bleach due to the degeneration of coral tissue and/or expulsion of zooxanthellae (see Appendix for coral images). However, a few of the pink branches were present over the entire survey period and bleaching associated with pink pigment regions was not observed. Therefore, those coral colonies are maintaining a state of stability and equilibrium. If the corals are exposed to further environmental stress, bleaching is likely to occur. If the coral remains resistant to bleaching, the zooxanthellae may once again repopulate the coral, returning the brown coloration.

The coral identified as J was recorded as bleached five months into the data collection. The week before the May 30th survey, Hanauma Bay experienced an extreme tidal change from -0.5 ft to 2.5 ft. During the lowest tide interval, the top portion of the coral may have been only a few inches underwater and the strong irradiance has been linked to bleaching (Jokiel and Brown, 2004). It is probable that the nearby corals did not experience any bleaching due to genetic differences or varying symbiont clades that are more resilient (Pettay and Lajeunesse, 2009; Morikawa and Palumbi, 2019).

Coral K had minute algal growth across the coral head. The cause of the algae infiltration is unidentifiable as well as the algal species. Obtaining coral tissue samples could give insight into the susceptibility of the coral head to algal settlement.

A few ImageJ measurements were not included in the surface area analysis due to photographic error. Some photo distortion occurred from tide differences and water movement and the misplacement of the lock altered the reference scale. However, qualitative observations from the first and last photos show most corals either losing tissue or remaining unchanged. The only corals with growth potential from the photos are B, E and L. The initial photos documented white branch tips, but later images show full brown tissue, which may indicate growth. One method of coral growth is through primary calcification, or skeletal extension at the coral tips (Fang et al., 1989). It is possible that primary calcification was rapid, and the zooxanthellae had yet to settle in the polyps.

### 4.3 Natural vs. Anthropogenic Disturbances

There were no documented coral breakage or new lesions from human disturbances. Although there were many reef contacts and high visitor numbers, low coral cover may explain why most of the corals remained untouched. For example, the KN plot is 25 $m^2$ and the only living coral in the plot (coral O), occupies approximately 0.03 $m^2$, representing <1% coral cover. However, if snorkelers notice a coral on the reef shelf, they may want to swim near it. It is plausible that visitors are more cautious with their behavior near a coral colony rather than the reef substrate that appears as rock. Hence, there was no indication of physical damage inflicted by humans.

Corals in the outside reef were documented with similar patterns as the inside reef: dead branches, fish bites, and heavy sediment load. Many corals offshore may be subject to heavy sedimentation due to extreme turbidity and waves that break along the reef shelf. The degraded coral health conditions could also be a product of other regional-scale stressors.

## 5.0 CONCLUSION

### 5.1 The Number of Snorkelers and Reef Disturbances

I hypothesized that high visitor activity in the nearshore plots would result in the most coral damage from physical contact. My hypothesis was not substantiated by the results since corals at all stations experienced tissue loss. Tissue loss was not evident as an outcome of human disturbance when compared with results from the offshore reference station. However, one of the nearshore plots, KN, had the highest visitation and reef disturbance frequency and very low coral coverage. Although the evidence for human disturbance is limited, previous human contact could have caused the current tissue damage noticed in the initial survey. Additionally, anthropogenic reef interactions may prohibit coral growth, reproduction, and larval settlement (Richmond, 1993; Mora et al., 2016). This is evident in Hanauma Bay, since limited coral growth and recruitment was observed for *Pocillopora meandrina*.

The far shore plot in Keyhole Lagoon had the second highest visitation and reef disturbances. It is reasonable to assume that many snorkelers entered the ocean from Keyhole Lagoon and swam over the near shore reef, then proceeded to swim to the far shore plot. Overall, few snorkelers visited Backdoor Lagoon. Only in instances when some snorkelers ventured to the East side of the bay did other snorkelers follow.

The ratio of one disturbance for every two snorkelers is based on the daily visitor cap. In December of 2020, Hanauma Bay only allowed 720 visitors to enter the park, but this increased to 1000 daily visitors in April of 2021. If the daily entrance increases to pre-covid conditions of 3,000 people per day, the occurrence of reef disturbances is anticipated to triple along with physical contacts directly to coral colonies.

## 5.2 Management Actions for Hanauma Bay

Since 2002, all visitors entering Hanauma Bay are required to watch a 9-minute educational video as a part of a conservation plan (Hanauma Bay History, HanaumaBay-StatePark.com). The video describes the importance of coral reefs, safety measures, and establishes the prohibition of touching or taking any marine life. Despite precautionary measures of the education team and staff at Hanauma Bay, there are still high numbers of reef contacts. Most reef disturbances occur as a product of poor snorkeling techniques (Harriot et al., 1997; Giglio et al., 2016; Luna et al., 2009; Webler and Jakubowski, 2016). Therefore, it is recommended for first-time snorkelers to remain in the sandy patches of the bay along reef shelfs where they can still view fishes and coral. The education staff can convey this message to visitors and adapt it as a park regulation.

The data represents only 2.5% of the total time Hanauma Bay is open per month. Therefore, the number of snorkelers entering each plot and the number of reef disturbances are likely to be significantly higher. It is possible that during the other 97.5% of the time, snorkelers contacted coral colonies, but the strong skeletal structure is the reason for unnoticeable lesions or abrasions. If that is the case, the morphology, robust branch structure, size, and density of the coral (Rodgers et al., 2003) could explain why *Pocillopora meandrina* is one of the only remaining coral species present on the inside reef of Hanauma Bay. Based on the results of Severino et al. (2020), expanding the number of daily visitors is likely to increase sediment resuspension. Moreover, physical reef disturbances from visitors are only a part of the narrative of coral degradation in the bay. The combination of physical disturbance (Lamb et al, 2014), high bacteria levels (Richmond, 1993), sunscreens (Danovaro et al., 2008), and runoff (Richmond, 1993) can cause poor coral health. Impaired health of corals in Hanauma Bay may limit future coral recruitment and affect the survival of other marine life in the nature preserve that depend on coral reefs (Bonin et al., 2009; Hourigan et al.,1988). Evidence of coral degradation can reduce tourist visitation and impact visitor expectancy (Le et al., 2019; Coghlan and Prideaux, 2009). The objective is to mitigate current human disturbances in Hanauma Bay, not to promote stressors to the marine life residing there by increasing visitor capacity and reef contacts.

A tide-gauge placed in the water at Hanauma Bay would be useful. Direct physical contact could be limited by prohibiting snorkeling once the tide reaches below a threshold of 0.7 ft (fig. appendix A.1). Lifeguards located in the four stands or volunteers can regulate this activity and communicate with snorkelers via loudspeakers across the beach. During this period of low tide, snorkeling can remain along the reef shelves in sandy patches located in Backdoor Lagoon, Keyhole Lagoon, and Sandman's patch. Snorkelers will still be able to view marine organisms along the shelf.

Another way minimize reef contacts is designating a meeting location if members lose contact in the ocean. Having this information in the educational video and at the *SeaGrant* kiosk on the beach can limit purposeful reef disturbances, especially sitting and standing on the substratum. If a snorkeler needs to locate their group, they need to first move to sandy seafloor to stand.

Hanauma Bay can experience rough conditions throughout the year and snorkelers need to be cautious during times of high wind and swell. The increased water motion throughout the bay can cause snorkelers to grab onto the reef to stabilize. During these circumstances, lifeguards should decide if visitors are limited to snorkeling along the reef shelf as in the low tide circumstance.

Future studies need to investigate the patterns of dead coral branches and associated reasons through examining zooxanthellae density, protein expression, and various genomic techniques. *Pocillopora meandrina* tissue loss has been studied in the bay previously, but the causation of tissue decline is still unknown (Walker, 2003 Dissertation). Tissue sampling of coral branches with pink pigmentation will help determine the microbial consortium of disease and if the coloration is strictly from chromoproteins. In the case of coral disease, determining the causation of the pathogen infiltration is an important aspect of minimizing tissue loss. Additional sedimentation and coral recruitment research may be a crucial part of coral recovery.

*Pocillopora meandrina* is a candidate under the Endangered Species Act. All coral species should be protected across Oʻahu and especially at Hanauma Bay Nature Preserve where visitors can learn about their importance and act accordingly. Corals face the effects of many global stressors that are predicted to increase. It is also important to control regional-scale impacts of human contact with the reef. If the goal is to maintain the current conditions for Hanauma Bay, the least managers can do is keep visitor counts the same. The new information provided in this study can allow managers to more fully understand human contact consequences to develop strategies to reduce them.

APPENDIX

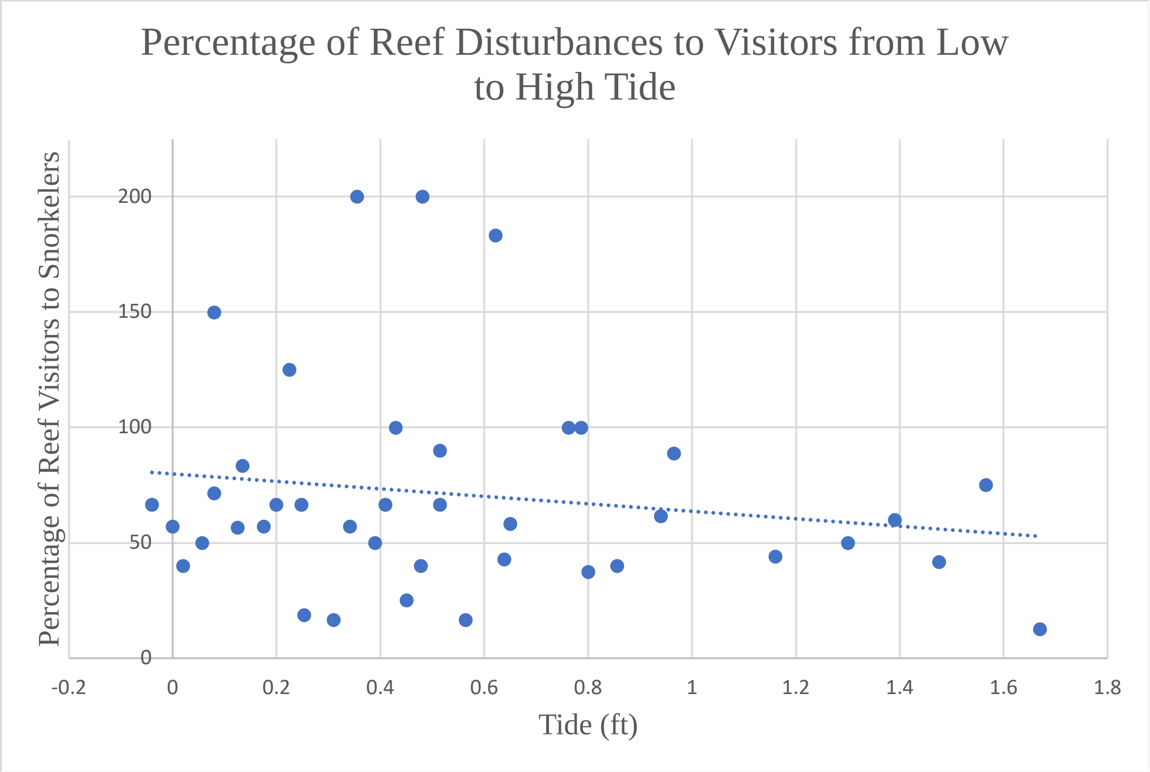

**Figure A.1. The ratio (in percentage) of reef visitors to the number of snorkelers for Keyhole Lagoon and Backdoor Lagoon combined. The ratio of disturbance to visitor frequency is separated by tide, ranging from approximately -0.05 ft to 1.7 ft. The data represents a slight decrease in disturbance as the tide increases, meaning the water becomes deeper over the reef shelf. The frequency of disturbance increases at a tide lower than 0.7 ft. Below 0.7 ft, the ratio is up to 200%, demonstrating that each person in the plot physically contacted the reef more than once.**

**Figure A.2. Coral A from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral A is located in the Backdoor Far plot (BF/1).**

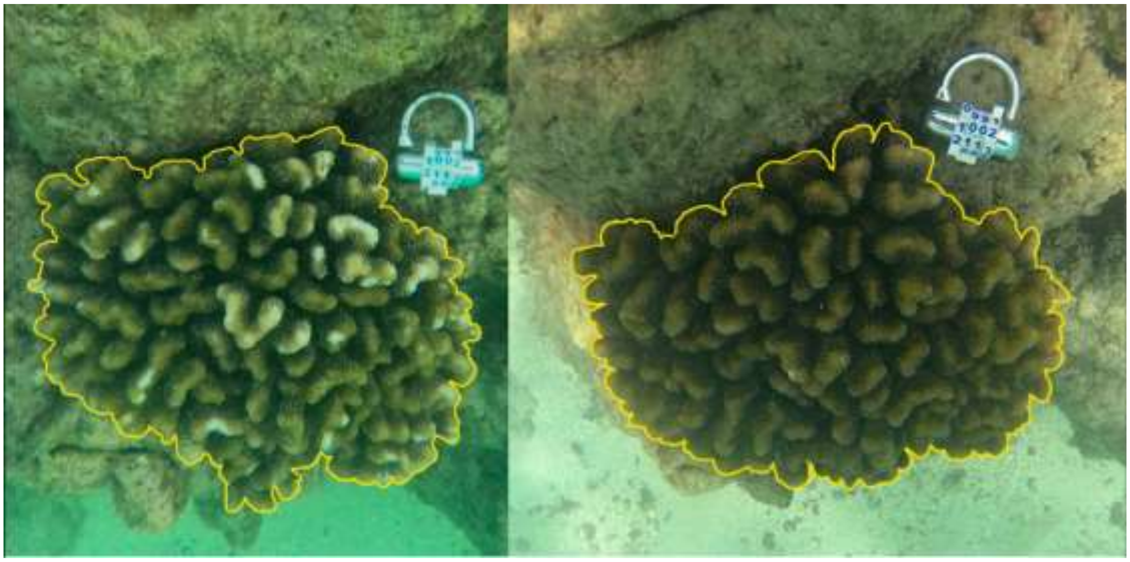

**Figure A.3. Coral B from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral B is located in the Backdoor Far plot (BF/1).**

**Figure A.4. Coral C from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral C is located in the Backdoor Far plot (BF/1).**

**Figure A.5. Coral D from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral D is located in the Backdoor Far plot (BF/1).**

**Figure A.6. Coral E from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral E is located in the Backdoor Far plot (BF/1).**

**Figure A.7. Coral F from the initial survey on December 4th, 2021 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral F is located in the Backdoor Far plot (BF/1).**

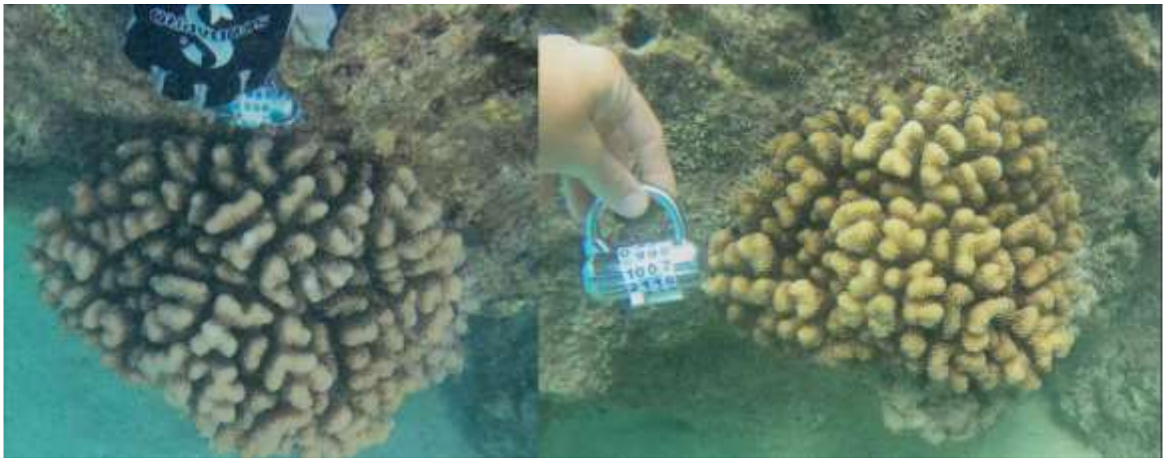

**Figure A.8. Coral G from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral was not used in ImageJ for the lack of substrate to place the lock on. Coral G is located in the Backdoor Far plot (BF/1).**

**Figure A.9. Coral H from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral H is located in the Keyhole Far plot (KF/3).**

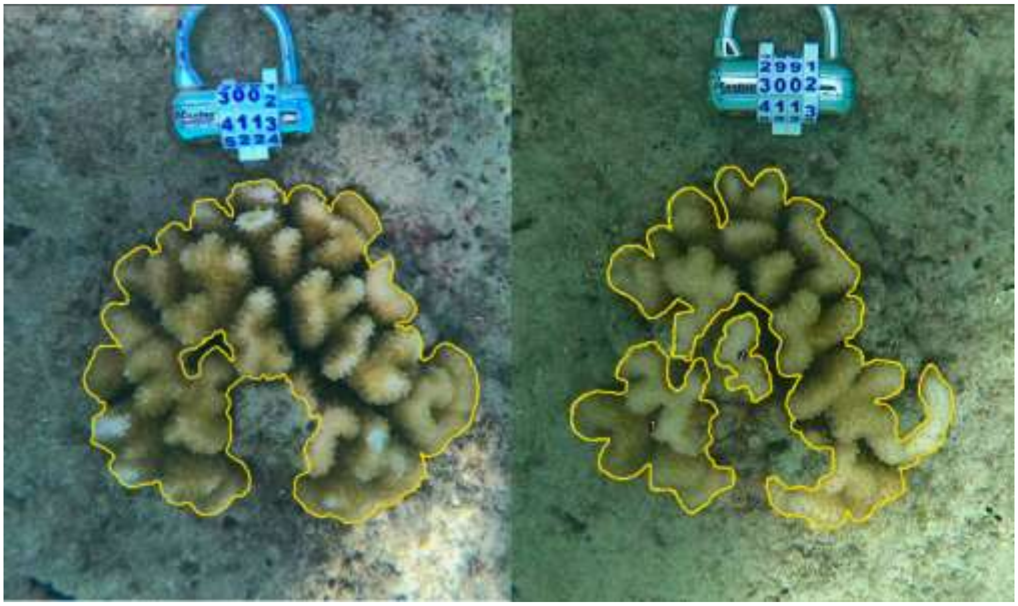

**Figure A.10. Coral I from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral I is located in the Keyhole Far plot (KF/3).**

**Figure A.11. Coral J from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral J is located in the Keyhole Far plot (KF/3).**

**Figure A.12. Coral K from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral K is located in the Keyhole Far plot (KF/3).**

**Figure A.13. Coral L from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral L is located in the Keyhole Far plot (KF/3).**

**Figure A.14. Coral M from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral M is located in the Keyhole Far plot (KF/3).**

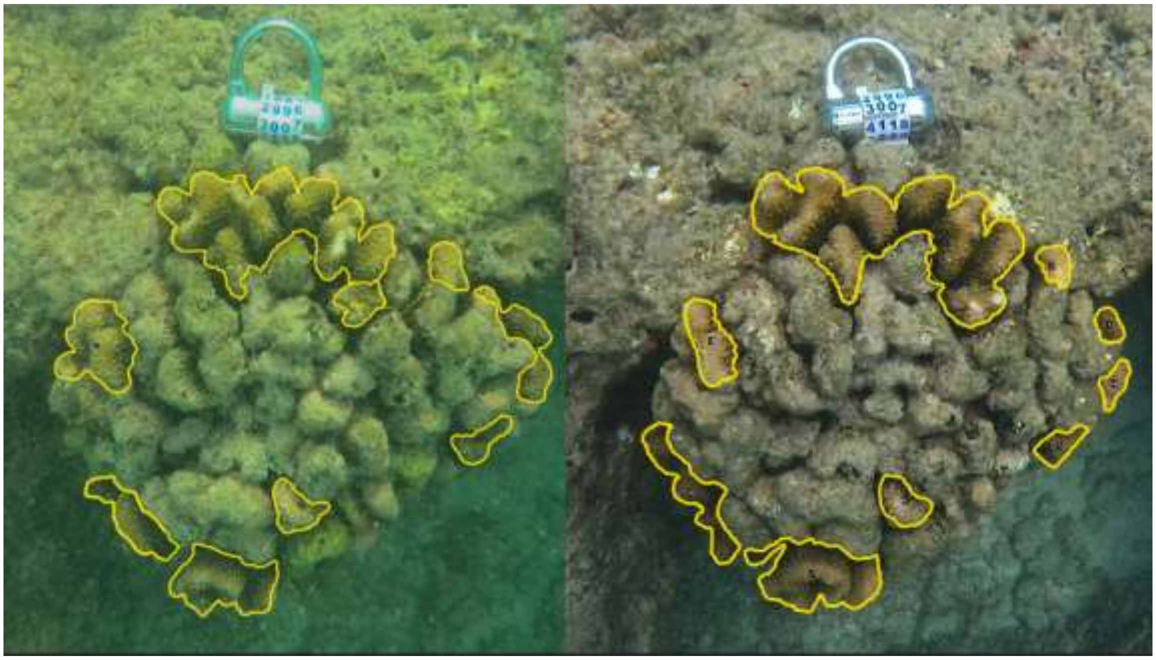

**Figure A.15. Coral N from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral N is located in the Keyhole Far plot (KF/3).**

**Figure A.16. Coral O from the initial survey on December 4th, 2020 (left) and the last survey on September 26th, 2021 (right). The coral is outlined for comparison of tissue growth and/or loss. Coral O is located in the Keyhole Near plot (KN/4).**

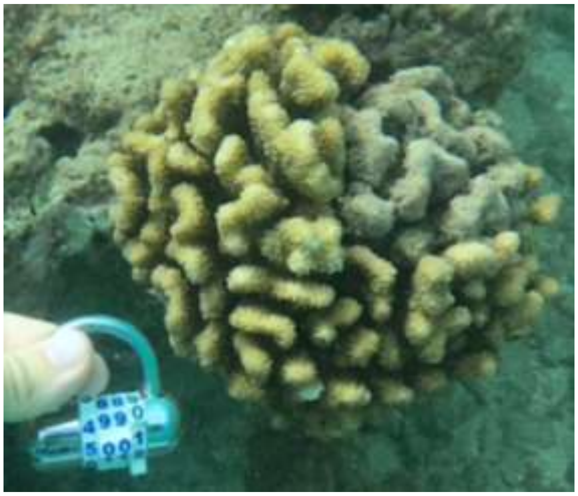

**Figure A.17. Coral P from the outside reef plot (OR/5) surveyed on September 26th, 2021.**

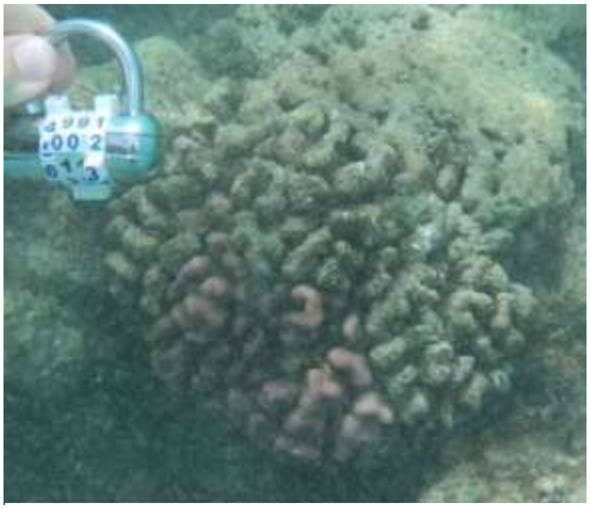

**Figure A.18. Coral Q from the outside reef plot (OR/5) surveyed on September 26th, 2021**.

**Figure A.19. Coral R from the outside reef plot (OR/5) surveyed on September 26th, 2021**.

**Figure A.20: Coral S from the outside reef plot (OR/5) surveyed on September 26th, 2021**.

**Figure A.21. Coral T from the outside reef (OR/5) surveyed on September 26th, 2021**.

**Figure A.22. Coral U from the outside reef (OR/5) surveyed on September 26th, 2021**.

**Figure A.23. Coral V from the outside reef (OR/5) plot surveyed on September 26th.**

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