Assessment of Biological Carrying Capacity at Kapoʻo in the Pūpūkea MLCD

Prepared for:
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Content

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Acronyms

BRT	Boosted regression trees
CCA	Crustose coralline algae
FAA	Federal Aviation Administration
ha	Hectare – equivalent to 2.5 acres
GPS	Global Positioning System
LLC	Limited liability corporation
LMM	Linear mixed model
MLCD	Marine life conservation district
MPA	Marine protected area
MPW	Mālama Pūpūkea-Waimea
SCUBA	Self Contained Underwater Breathing Apparatus
UAV	Unmanned aerial vehicle

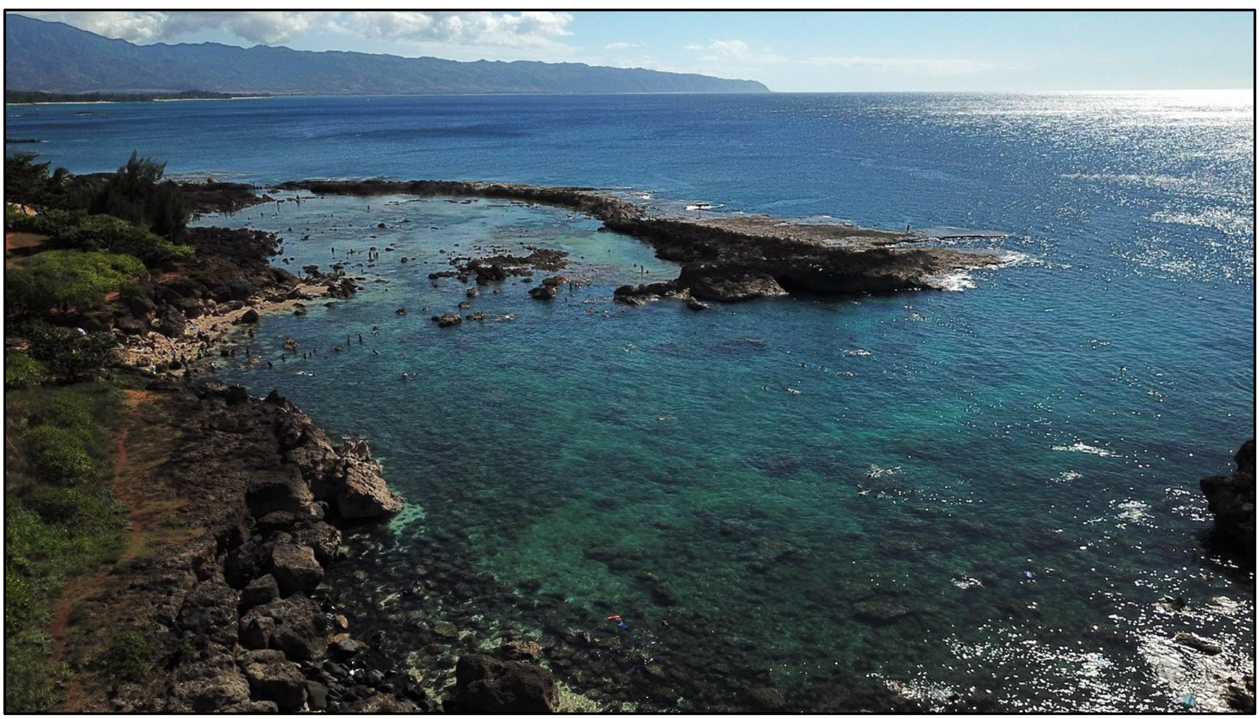


Figure i. Kapo'o seen from above with the Cove in the foreground and the Tidepool behind. Photo credit: Rob Walker, Shoreline Conservation Initiative.

Key Findings

Human usage

- Visitor use of the Tidepool and Cove was highest between 10am – 5pm, with peak usage from 12pm – 3pm. The Cove was more popular in the morning hours with the Tidepool seeing higher visitation in the afternoons.
- Visitor counts in the Tidepool and Cove combined were relatively consistent throughout the week with peaks on Thursday and Saturday.
- By comparing the average monthly visitor counts we see a shift from Tidepool to Cove in the summer months with Tidepool visitor numbers peaking in March and April. Overall (Tidepool and Cove combined) visitation increases in January through March and remains relatively consistent from March to September.
- The highest human densities were observed near the main entrance to the Tidepool, followed by the deeper area in the center of the Tidepool. The main access to the Cove was another area of high human density.

Marine life and human effects

- The presence of humans within a 10 m radius had a significant negative effect on fish abundance and fish species richness.
- The greatest declines in fish abundance and species richness were for one human within 10 m for abundance and two humans within 10 m for richness. When there were four or more humans within 10 m, both fish abundance and species richness were minimal.
- Fish abundance and species richness were higher in the Cove compared to the Tidepool.
- Mobile invertebrate abundance (primarily rock-boring urchins) showed a negative effect of humans standing within 10 m, though the total number of humans within 10 m had no effect on either mobile invertebrate abundance or species richness.
- Turf algae was the predominant living benthic cover on all transects, followed by crustose coralline algae (CCA). CCA was more common in the Cove compared to the Tidepool. Coral was found in small proportions on most transects.
- Coral impact surveys revealed damage in 66% of surveyed colonies. Human density had a significant effect on probability of coral damage which increased from 50% in areas with low human density to 80% in areas of high human density.
- 25% of all visitor substrate contacts recorded were on algae (turf, CCA, macroalgae) and 5% were on corals.
- SCUBA divers had the highest average number of substrate contacts and coral contacts (3.4) per dive, followed by snorkelers. However, snorkelers had a much lower incidence of coral contact (0.5).

Management implications

- Based on the human density threshold for fish abundance, biological carrying capacity estimates range from 15 – 41 for the Tidepool and 5 – 35 for the Cove

Introduction

Marine protected areas (MPAs) provide a range of benefits to humans, including providing recreational and tourism opportunities. However, like other human activities, tourism can have environmental impacts. Damage to corals and other species from divers and snorkelers are among a range of tourism impacts documented in MPAs worldwide. Mitigating these impacts is a key aspect of MPA management and the key is assessing the number of tourists and other visitors an MPA can support – it's carrying capacity. This term originated in ecology and represents the number of organisms an area can support over a specific time period. For tourism management, it has a similar meaning; the number of people an area can support without unacceptable impacts to the environment. Under too much pressure from visitors, the ecosystem and/or physical attributes of a site can degrade making it less attractive to tourists.

The World Tourism Organization and the UN Environmental program provide a basic equation for calculating visitor carrying capacity based on the space a tourist requires for an acceptable experience in the protected area. This approach is human-centric and very subjective as it is based on human perceptions which are highly variable. Another approach focuses on the degradation of the natural environment and organisms as a function of visitation. This is the basis for a number of studies on carrying capacity of recreational scuba divers which compare coral damage in different sites with known levels of diving (Hawkins and Roberts 1993, Hawkins et al. 1999). While terminology varies in the literature, this approach using biological indicators (also known as environmental carrying capacity) is referred to as 'biological carrying capacity' in this report as distinct from 'social' carrying capacity which relies on human perceptions.

Researchers have used a variety of indicators to determine biological carrying capacity in MPAs. Numerous studies focused on the impacts of recreational SCUBA diving typically use coral damage and cover with skeletal breakage as the most frequently documented impact, followed by loss of live coral cover and shifts in benthic assemblage composition (Giglio et al. 2020). Studies on the effects of reef walkers have used the same or similar indicators (Rodgers and Cox 2003, Leujak and Ormond 2008, Williamson et al. 2017), though (Neil 1990) measured sediment deposition. In contrast, apart from fish feeding, few studies have examined direct visitation impacts on coral reef fishes. Those that did used common fish assemblage measures such as abundance and species richness, with some finding little to no impact (Hawkins et al. 1999, Claudet et al. 2010) and others showing shifts in abundance and assemblage structure (Dearden et al. 2010, Albuquerque et al. 2014, Filous et al. 2017). Fish flight behavior, typically measured in the context of fishing pressure, is an emerging indicator that has been proposed to measure visitor impacts in MPAs (Samia et al. 2019, Stamoulis et al. 2019). Finally, the negative impacts of sunscreen on coral reef organisms are now starting to be explored (McCoshum et al. 2016, Wood 2018, Corinaldesi et al. 2018).

The state of Hawaiʻi is a global tourist destination with most visitors traveling to the island of Oʻahu. In 2019, 4.5 million tourists visited Oʻahu and an estimated 80% of them participated in ocean recreation activities (DBEDT 2013). The Hanauma Bay Nature Preserve on the south shore of Oʻahu is the most popular tourist visitor snorkeling destination in the Hawaiian Islands. A study of biological carrying capacity of Hanauma Bay was conducted from 2019-2021 over the extended closure due to the COVID-19 pandemic (Severino et al. 2021). This study found coral breakage and sediment accumulation increased with increasing visitor presence while water clarity decreased. During the closure, mean fish density increased while green turtle and monk seal abundance was not affected (Severino et al. 2021).

After Hanauma Bay, the next most popular tourist visitor snorkeling destination is the Pūpūkea Marine Life Conservation District (MLCD) on the north shore of Oʻahu. Pūpūkea MLCD includes three sites with different habitat characteristics, accessibility, and use levels: Waimea Bay, Three Tables, and Sharks Cove. Needham et al. (2008) investigated social carrying capacity and visitor perceptions at Pūpūkea MLCD using visitor surveys and, while overall satisfaction was high, they documented perceived crowding at the Sharks Cove site. Sharks Cove is traditionally known as Kapoʻo and includes a shallow (0-2 m) tidepool area and deeper (1-5 m) cove. In one of the few studies to examine marine recreational impacts in Hawaiʻi, Meyer and Holland (2008) measured substrate impacts of divers (SCUBA and snorkelers) at four Hawaiian MPAs, including Pūpūkea MLCD, and found a low level of substrate impact primarily from shore-based users.

Mālama Pūpūkea-Waimea (MPW,) a marine stewardship non-profit, was established by community members in 2005 to provide outreach and education and care for the marine life of the MLCD. Since 2012, MPW has commissioned and collaborated on a number of scientific and citizen science surveys to better understand the status and threats to the area's marine life and recently drafted the first management plan for the area. Informed by this experience and data and in response to increasing visitation and a continued decline in marine life abundance and health, MPW commissioned this study to investigate biological carrying capacity in the Kapoʻo area of the Pūpūkea MLCD. In parallel with the current study, MPW was successful in passing legislation (Hawaii state Act 31) to fund a pilot program to assess biological carrying capacity. The pilot program is currently underway and builds on the approach and findings of this research.

This study was led by Seascape Solutions LLC in partnership with the 2022 MPW Marine Science Coordinator (Jones 2022) with the aim to implement human use and biological data collection with high enough spatial and temporal resolution to explore causative relationships in high-use areas of the Pūpūkea MLCD, the Kapoʻo Tidepool and Cove. The goal is to use these study results to help determine ranges and/or thresholds of acceptable impacts which can be linked to visitor numbers for management. Specifically, this study addressed the following questions:

1. How do visitor numbers correspond to marine life abundance and health?
    a. What are the patterns of visitor use in time and space?
    b. How are fishes affected by visitor presence?
    c. How are corals affected by visitor presence?
2. What is the threshold number of visitors beyond which marine life are highly impacted, the biological carrying capacity?

Methods

This study draws upon data collected between January 2022 and September 2022. Study and survey design, training, data management, analysis, and reporting were conducted by Seascape Solutions. Data collection was carried out by the 2022 MPW Marine Science Coordinator Ellie Jones, Keelan Barcina (2021 MPW Marine Science Coordinator) assisted with human-use counts, a team of marine science students tracked visitors, and UAV/drone surveys of human use patterns were conducted by Shoreline Conservation Initiative.

Two general types of biological indicators were investigated in terms of impacts from human use at Pūpūkea MLCD, mobile fishes and invertebrates and sessile benthic organisms (corals and algae). Because they are mobile, impacts from human use on fishes and mobile invertebrates are temporal or behavioral in nature. Fishes are likely to vacate an area when too many humans are present or change their behavior in other ways. For this reason, temporal patterns of fish abundance were compared with human use via paired surveys, across a range of human densities. In contrast, corals and algae are non-mobile and impacts from human use are spatial in the sense that they are based on long-term exposure so that high human use areas will tend to have more impacts. Spatial patterns of impacts on benthic organisms were, therefore, compared with maps of human use to determine potential causative relationships while also accounting for natural driving factors. Turbidity (water clarity) was also measured as a variable influencing fish counts. Also, it has previously been shown to correlate with human usage at Hanauma Bay and has potential implications for the health of marine organisms.

For both types of biological indicators, patterns of abundance, growth, and/or impacts were compared across a gradient of human use while accounting for natural driving factors. In this way, the study was designed to explore the relationship between the health of marine organisms and the number of people present in their habitats. By quantifying the relationships between number of visitors and effects on the biological community, managers will be better equipped to make decisions about what level of impact is acceptable and design appropriate strategies to limit human use.

A range of methods were employed to quantify and map human use and its impacts on abundance and diversity of marine organisms. Overall human use was quantified with land-based visitor counts and spatial patterns and impacts were mapped using unmanned aerial vehicle (UAV, or “drone”) surveys and in-water visitor tracking. Marine life was surveyed using transects for fish, mobile invertebrates, and sessile organisms. Coral occurrence and impacts were surveyed separately using a roving survey method. See details on each of these methods below.

Human usage

Visitor counts

Visitor monitoring has been carried out by MPW for many years. These surveys represent point-in-time (snapshots) of visitor numbers in different zones categorized by activity type. Environmental conditions are also documented, including moon phase, tide, weather, wind and surf. The Kapoʻo Tidepool and Cove are among the zones monitored and visitor numbers were categorized by swimmers in water (no mask), snorkelers in water (mask), SCUBA divers, watercraft, as well as visitors on land in different areas. Because this study focuses on impacts of humans on marine organisms, only in-water human use counts were considered. For this study, visitor monitoring was conducted by Ellie Jones and Keelan Barcina.

Data analysis
Human use count data was summarized by hour, day of the week, and month. Hourly averages revealed higher usage in the late morning and afternoon hours (10 am – 5 pm), and the data was filtered for these high-use hours for subsequent comparisons when averaging by days and months.

Visitor mapping by drone

A total of six unmanned aerial vehicle (UAV) surveys were conducted by Shoreline Conservation Initiative to map human use patterns. Each UAV flight was conducted during high-use times from 10am-5pm and alternated between high and low tide conditions to account for variation in human use based on water depth.

A small UAV, DJI Mavic Pro, was used to conduct low-altitude flights over the study area – Kapoʻo Tidepool and Cove. The UAV was equipped with an external camera to collect imagery of the study area: 1/2.3" CMOS sensor with a total pixel count of 12.71M. Visible light imagery was captured with a 70% overlap between images allowing the collection of photographic data for the entire study area at high resolution.

The mobile phone software, Pix4Dcapture, was used to design flight plans based on grid patterns that ensured consistent coverage of the survey area and allowed for autonomous flight operation. The software was utilized to design missions consisting of grid pattern flight paths along parallel lines above the tide pool, considering camera specifications (e.g., Field of View) and optimizing flight characteristics (e.g., altitude, speed, and camera orientation) to ensure sufficient overlap of images as needed to create a complete composite visual mosaic.

Each survey was flown at an elevation between 90-120 meters which was determined by factors of UAV camera resolution, maximum flight elevation rules, battery life, and ground coverage. Flight lines were designed to create a 70% overlap, resulting in over 60 images per flight to cover the entire tidepool and cove area. Flight missions were designed such that the UAV would autonomously navigate into position and then stop momentarily to capture each image to reduce speed blur and camera angle offset. Flights avoided the noon hour to reduce the amount of sunlight reflection in images.

In general, all flights were overseen by an FAA-licensed UAV pilot with additional researchers assisting with flight operations. This allowed for one person to fly the UAV, and a second person to initiate the flight software as well as maintain a continuous line of sight to the UAV during the flight. A total of ten survey flights were conducted to achieve six composite images of sufficient quality for human use mapping. Aerial drone surveys representing the final surveys were conducted on the dates and times shown in Table 1, targeting different tide conditions to account for potential variation in human use patterns due to water depth. For the surveys on 8/24 and 8/31, two surveys were flown to mitigate potential glare issues near the noon hour.

Table 1. Flight times

Date	Time start	Time stop	Tide level
7/27/2022	3:41 PM	3:50 PM	1.7 ft
8/16/2022	3:47 PM	4:02 PM	1.1 ft
8/24/2022	1:43 PM	1:54 PM	1.7 ft
8/24/2022	2:01 PM	2:14 PM	1.7 ft
8/31/2022	10:30 AM	10:46 AM	0.6 ft
8/31/2022	11:03 AM	11:18 AM	0.6 ft
9/7/2022	2:00 PM	2:14 PM	1.7 ft
9/12/2022	10:55 AM	11:10 AM	0.5 ft

Image data analysis

The software Agisoft Metashape was utilized to generate composite geo-referenced image mosaics in geotiff format of the entire study area for each survey. These image mosaics were then imported into ArcMap software (ESRI) to map and quantify in-water visitor presence. A point shapefile was created corresponding to each survey image which was systematically searched using a grid overlay and points were placed at each in-water human location zooming in to at least 1/200 scale. Humans were categorized as swimming/floating or standing. Each survey image/shapefile pair were checked by two independent observers. A kernel density surface was then created for each shapefile in ArcMap using a hectare area unit with a 30m search radius and output cell size of 1 m^2. The six kernel density rasters were then averaged to derive the final human density surface used for analysis.

<u>Visitor tracking</u>

Visitor tracking methods followed (Meyer and Holland 2008) where observers equipped with snorkeling gear, a data slate, and a GPS unit followed individuals for the full duration of their in-water activity from point of entry to point of exit from the intertidal zone. Observers aimed to blend in with the crowd and remain undetected by their subjects. Activities surveyed include snorkeling (mask), swimming (no mask), wading, and SCUBA diving. In addition to tracking each visitor with the GPS, observers also collected waypoints to document all substrate contact.

Substrate contacts were categorized by substrate type and which body part made contact. For waders, only contact with live substrates was recorded. Visitor tracking surveys were carried out by a team of University of Hawaii marine science students: Caroline Smith, Tom Matsuyama, Sydney Cook, Eliza Beckwith, Allison Sommer, Nicole Makar, Giulia Marenco di Moriondo, and Jia Cashon. In addition, Giulia Marenco di Moriondo provided logistic and field support.

At the end of each survey day, the data from each GPS unit was downloaded and backed up and observers entered their survey data into an online database. The GPS track data was separated into unique surveys using survey start and end times and the GPS substrate contact waypoint data was joined with the associated data in the database. The tracking data was summarized by mean duration and distance for each activity type. The substrate contact data was summarized by the mean number of contacts by substrate type, for each activity type.

Marine life

Fishes and mobile invertebrates

Eight ʻpermanent' (10x4m) transect locations were distributed in Kapoʻo Tidepools and Cove, respectively, for a total of sixteen transects (Fig. 1). Locations were generally be based on those surveyed in 2021 with the modification that all transects occurred over hard-bottom substrate (>50%) and incorporated key locations identified by the community. Chosen locations were between 0.2 – 2.0m in depth to represent shallow areas where visitors were more likely to contact the substrate and adequately spaced from other transects to provide independent samples (> 20 m spacing between start points to ensure no overlap). Transect start point GPS coordinates and compass bearings were documented to ensure replication. Transects in both zones were surveyed weekly from June to September 2022 by Ellie Jones (the observer). To ensure variability in human use (which is lower in the morning hours), the order in which zones were surveyed was alternated weekly. Human use surveys following the established MPW protocol were conducted immediately prior to and following in-water surveys in each zone (Tidepool & Cove). Each transect was surveyed consecutively and in the same order.

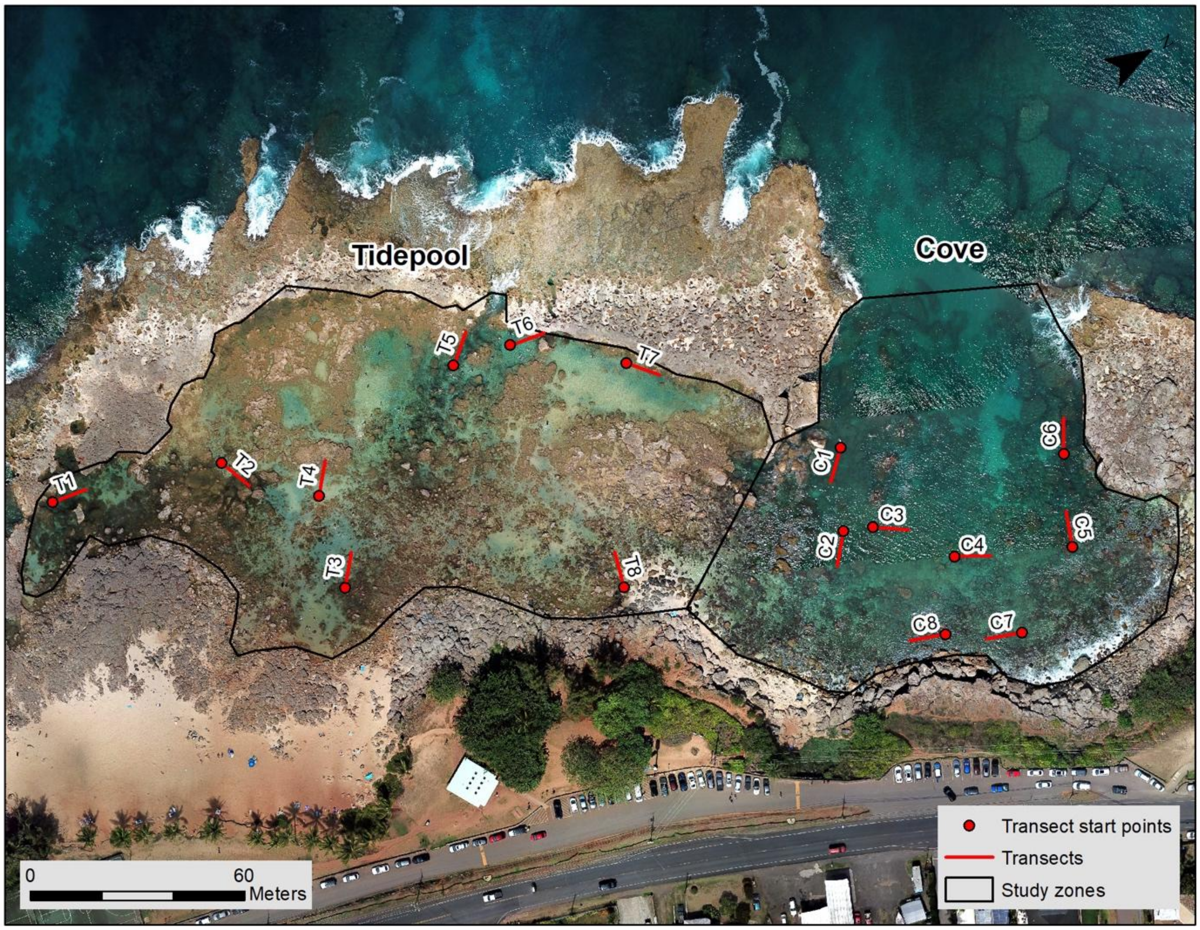


Figure 1. Transect locations for fish, mobile invert, and benthic surveys.

To conduct the surveys, the single observer, equipped with snorkeling gear, a data slate, and an underwater camera, navigated to the transect start location with GPS. Before initiating the survey, human activities (number and type) within a 10m radius from the transect center were recorded and photographed, making a distinction between those standing and swimming. Depth was measured with the transect line and recorded, then the transect line was securely attached to the substrate. After noting the start time, the observer slowly advanced along the 10 x 4m transect in the established direction (using a compass if necessary), reeling out line along the way, and identified and counted all fishes visible within 2 m to either side of the centerline. Time spent on each transect was ~5 min and care was taken to make sure transect line was straight and taut. Fish species unable to be identified in the field were photographed for later identification. In addition, the number, activity, and duration of any humans occurring within the transect area during the 5 min survey period were recorded.

Upon completion of the fish count, the observer placed the transect reel on the substrate and then reversed direction and counted all mobile invertebrates (sea urchins, sea cucumbers, crabs, etc.) occurring within 2 m to either side of the centerline along the transect during a 5 min period. When the mobile invertebrate count was completed, a measurement of horizontal water visibility/clarity was conducted using a Secchi disk. Then the observer reeled in the transect line and proceed to the next transect location. All survey data was input into a purpose-built Microsoft Access database.

Data analysis

Fish and mobile invertebrate data were summarized in terms of mean abundance and richness per transect. Species with high abundance were listed along with mean abundance values to aid in the interpretation of subsequent analyses. Linear mixed models (LMMs) were used to compare the paired human counts with the following response variables: Overall fish abundance and species richness, fish herbivore (primary consumer abundance), fish secondary consumer (exclusive of piscivores) abundance, overall mobile invertebrate abundance and richness, and abundance of rock-boring urchins of the family Echinometridae. All response variables were transformed to meet assumptions of normality and all explanatory variables were scaled and centered prior to analysis. Fixed factors included Zone (Tidepool or Cove), water depth, water clarity (horizontal Secchi disk measurements), humans swimming within 10 m of the transect center, humans standing within 10 m of the transect center, humans swimming on transect, and humans standing on transect. Transect number was included as a random factor to account for inherent differences in location/ natural context. A Spearman correlation analysis was conducted for all explanatory factors and the highest correlations were between the number of swimmers at 10m and on transect (ρ=0.38) and standers at 10m and on transect (ρ=0.35), suggesting some redundancy between these metrics. Depth was positively correlated to swimmers and water clarity. Water clarity was negatively correlated with human metrics. Following the first round of models, humans swimming and standing within 10 m were summed to create a single human variable, transect counts were dropped as a factor, and a second round of LMMs were run for the same response variables.

To determine potential thresholds in human density for fish abundance and richness, boosted regression tree models (BRTs) were fit using total humans within 10 m of the transect center, water depth, water clarity, and transect number. Model fitting and selection were accomplished following the procedures detailed in Elith, Leathwick & Hastie (2008). Fish abundance and richness were modeled with a Gaussian distribution and a fourth root transformation was applied to improve normality. Due to the low number of predictor variables, model simplification was not necessary. Model fit was evaluated using cross-validated percent deviance explained. Partial dependence plots for human density, showing its relationship with the response variable when other variables are at their mean, were used to identify values resulting in the largest drops in fish abundance and biomass.

Coral and algae

Transect surveys

Benthic surveys took place on the same transects as the fish and mobile invertebrate surveys (Fig. 1). Three replicates of 16 transects (8 in each zone) were completed between July and September 2022 by Ellie Jones (the observer) on snorkel. Benthic cover was quantified using a quadrat-based point intercept method where substrate types under each of 16 intersections of a 0.5m x 0.5m quadrat were recorded for each of the ten quadrats, resulting in a total of 160 points per transect.

To conduct the surveys, the observer equipped with quadrat, data slate, and underwater camera, navigated to each transect start location using GPS and filled out metadata including transect number, date, time, etc. A photo was then taken of the datasheet to help organize subsequent photos. Depth was measured with the transect line before fastening to the substrate. Then the entire 10m transect line was reeled out and made fast on the reef.

The observer then proceeded with the benthic cover surveys by identifying substrate types on each of 16 intersections on a 0.5m x 0.5m quadrat, for a total of 10 quadrats per transect on alternating sides of each 10m transect line. The first quadrat was placed along the right of the transect line so that the bottom edge of the quadrat aligned with the transect start. The quadrat was then photographed before identifying any substrate occurring directly below each of the 16 intersections to the lowest possible taxa and noting on the datasheet. For transects T6 & T7 (Fig. 1) all quadrats were placed on the west side of the transects to focus on live-cover areas. Benthic survey data was input into a purpose-built Microsoft Access database. Quadrat photos were not analyzed but catalogued as a permanent record.

Data analysis

Benthic cover data was averaged across the three surveys to generate mean values for each transect and relative proportions of living cover types were mapped to show spatial variation. In addition, coral species were summarized in terms of mean percent cover. Multivariate linear regression was used to compare the UAV-derived human density values at each transect location with percent cover of corals, macroalgae, and (non-coral) sessile invertebrates. All response variables were transformed to meet assumptions of normality and all explanatory variables were scaled and centered prior to analysis. Explanatory variables included Zone, depth, and number of humans per hectare.

Roving coral survey

The objective of the roving count was to methodically survey the study area using a regular search pattern to locate coral colonies and identify visitor impacts to coral. This survey was conducted by Ellie Jones (the observer) over two days in mid-September 2022. To conduct the survey, the observer equipped with a GPS unit in tracking mode, data slate, and underwater camera, began at one end of the study area and swam methodically back and forth aiming to cover the entire Tidepool and Cove area up to ~2m in depth. Wherever a coral colony > 10cm (living or dead) was observed, it was identified to species and a GPS waypoint and photo were collected. Depth of the coral at its highest point and coral diameter along the longest axis in 5cm size bins were measured and recorded. Any visible damage was documented and classified by type (break, scrape, scrub - algae covered) and diameter (in cm along the longest axis) of the damaged area was recorded.

Data analysis

Roving coral survey data was summarized in terms of coral species, size, and depth. Coral damage was summarized in terms of type and size. Coral status (alive, half-alive, dead) and occurrence (presence/absence) of damage were mapped to visualize spatial patterns and overlaid on the UAV human density map. The relationship between human density and coral damage was tested using binomial logistic regression including depth and coral size as factors. As coral size was not a strong predictor, it was excluded from the final model. Coral species was initially considered as a factor but was not included due to unbalanced sample sizes as most corals recorded were *P. meandrina*.

Figure 2. A) Typical human use in the Tidepool, B) substrate contact with water shoes, and C) substrate contact with fins. Photo credit: Ellie Jones.

Carrying capacity

To extrapolate the human density threshold calculated for fishes (see Results) to the area of each study zone and define the biological carrying capacity for management, several area measures were considered ranging from larger to smaller:

1. The total area delineated in satellite imagery as the water line around the perimeter of each zone with the seaward limit of the Cove considered as the narrowest point of the Cove mouth (Fig. 1). This measure includes all rocks protruding above the water's surface within each zone.
2. The area at low tide as delineated at 1:200 scale using drone imagery captured at (0.5 m) low tide. This measure excludes the shoreline and rocks exposed at low tide.
3. The area with the majority (90%) of humans based on the human density surface derived from the drone surveys, as a subset of the area at low tide described above.
4. The area of high human density based on the human density surface derived from the drone surveys and the identified human density threshold for fishes, as a subset of the area at low tide.

The calculated human density threshold for fishes (number of people per hectare) was multiplied by each of the above area (hectare) estimates to calculate a range of carrying capacity estimates for management consideration.

Results

Human usage

<u>Visitor counts</u>
This analysis focused on in-water human use which is most relevant to marine species. All values represent point-in-time or snapshot counts, ie. the number of visitors at a single point in time.

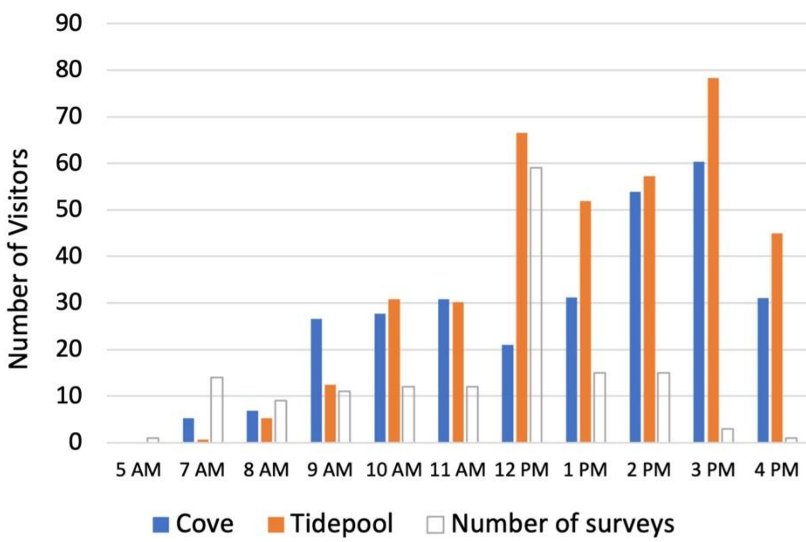


Figure 3. Average number of visitors (at a single point in time) in the Cove and Tidepool by hour.

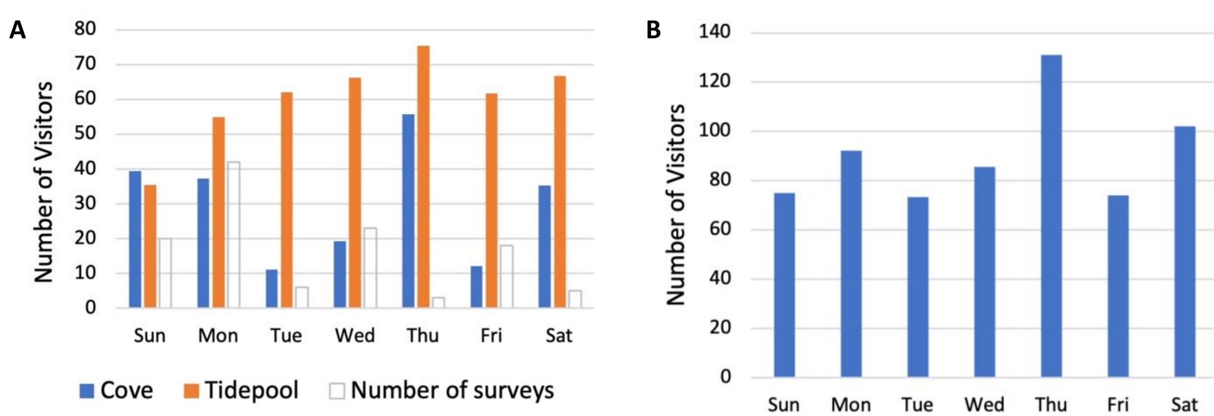


Figure 4. Average number of visitors (at a single point in time) in the Cove and Tidepool separately (A) and combined (B) by day of the week. Data filtered for high-use times 10am-5pm.

Survey effort was relatively consistent between 7am – 2pm, around 10-15 surveys over the study period, except for 12pm which had around 60 surveys (Fig. 3). Visitor use of the Tidepool and Cove was highest between 10am – 5pm, with peak usage from 12pm – 3pm. The Cove was more popular in the morning hours with the Tidepool seeing more visitation in the afternoons (Fig 3).

To compare human usage by day of the week, only data for high use times (10am – 5pm) were included in the analysis. Visitor counts in the Tidepool were lowest on Sundays and increased through the week, peaking on Thursday (Fig. 4A). Visitor counts in the Cove varied throughout the week and peaked on Thursday (Fig. 4A). Visitor counts in the Tidepool and Cove combined were relatively consistent throughout the week with peaks on Thursday and Saturday (Fig. 4B). Note that counts for Thursday are an average of just three surveys.

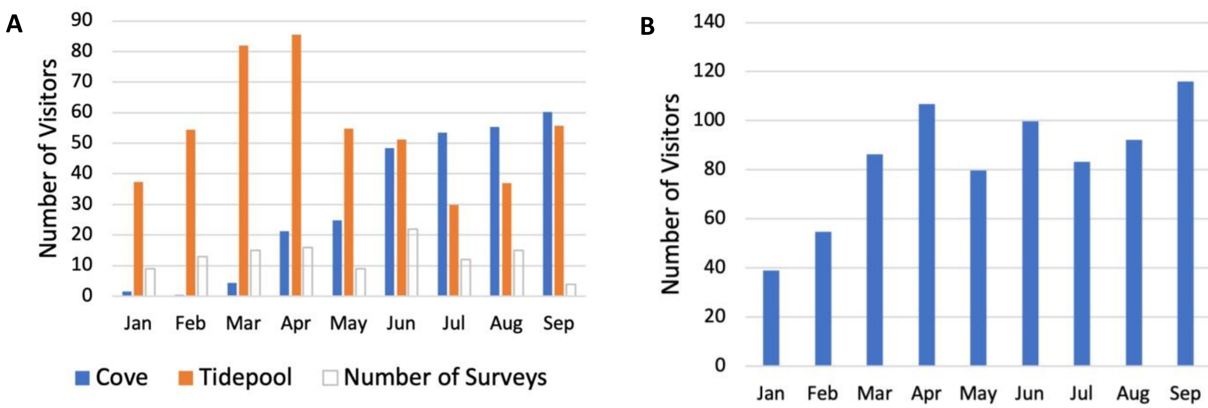


Figure 5. Average number of visitors (at a single point in time) in the Cove and Tidepool separately (A) and combined (B) by month. Data filtered for high-use times 10am-5pm.

By comparing the average monthly visitor counts we see a shift from Tidepool to Cove in the summer months (Fig. 5A). Tidepool usage peaks in March and April. Overall (Tidepool and Cove combined) visitation increases in January through March and remains relatively consistent (80-120) from March to September (Fig. 5B).

<u>Visitor mapping by drone</u>

UAV surveys and human use mapping showed humans distributed throughout both the Tidepool and Cove and identified locations with higher human densities (Figs. 6, 7). The percentage of floating vs standing individuals at the time of the surveys ranged from 53% - 62% with a mean of 57% (Fig. 6). The highest human densities were observed near the main entrance to the Tidepool, followed by the deeper area in the center of the Tidepool. Another area of high human density was in front of the main entrance to the Cove (Fig. 7). Apart from these key areas, visitors frequented the entire seaward portion of the Tidepool from the rocky pools at the south end to the sandy area at the north end, and the shallow area just south of the Cove entrance. In the Cove, most visitors stayed close to the southern margin directly offshore from the main access.

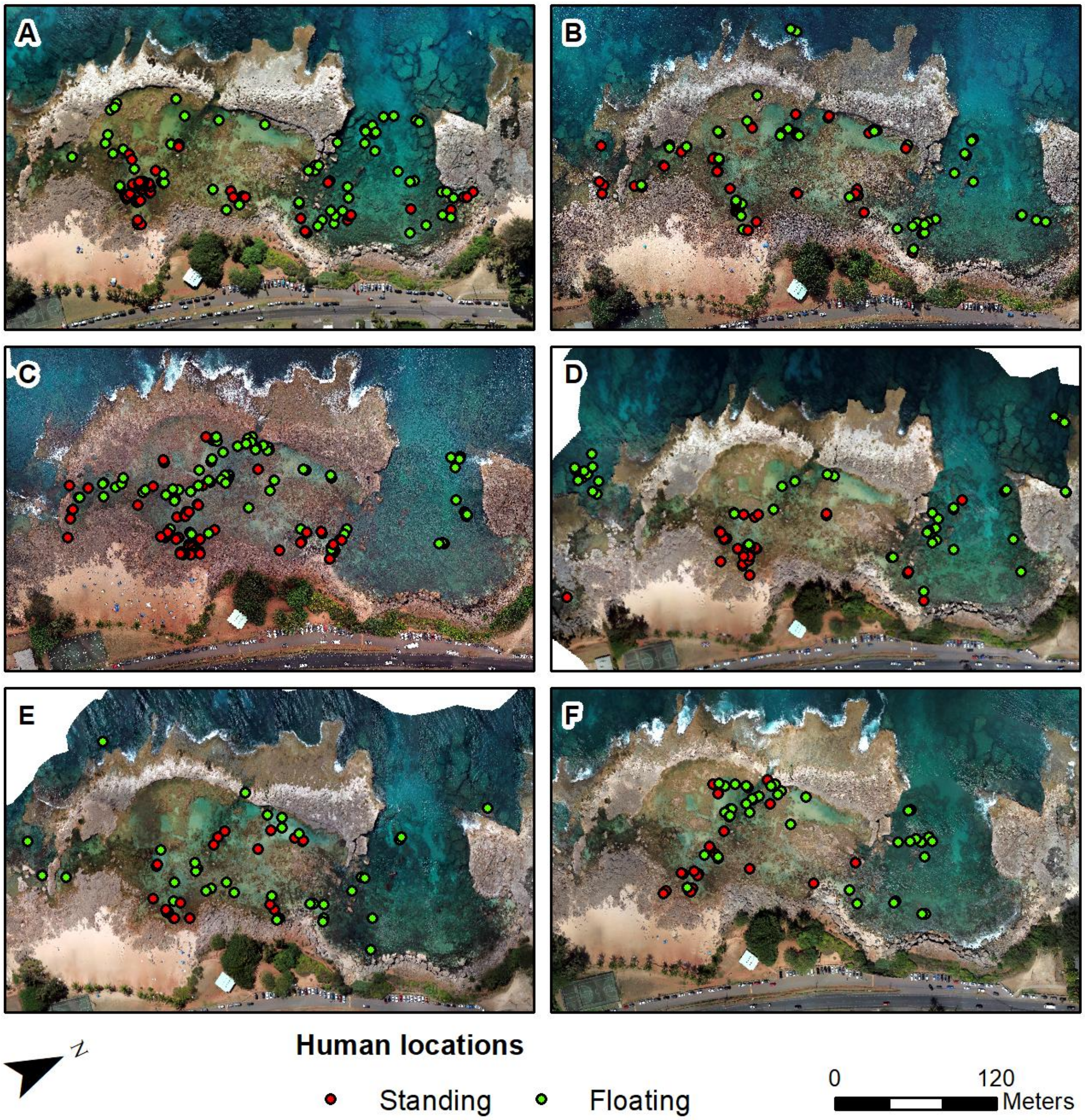


Figure 6. UAV imagery and human maps for each survey in 2022 A) July 27, B) August 16, C) August 24, D) August 31, E) September 7, and F) September 12. A), C), and E) represent higher tide/water levels and B), D) and F) represent lower tide/water levels (Table 1).

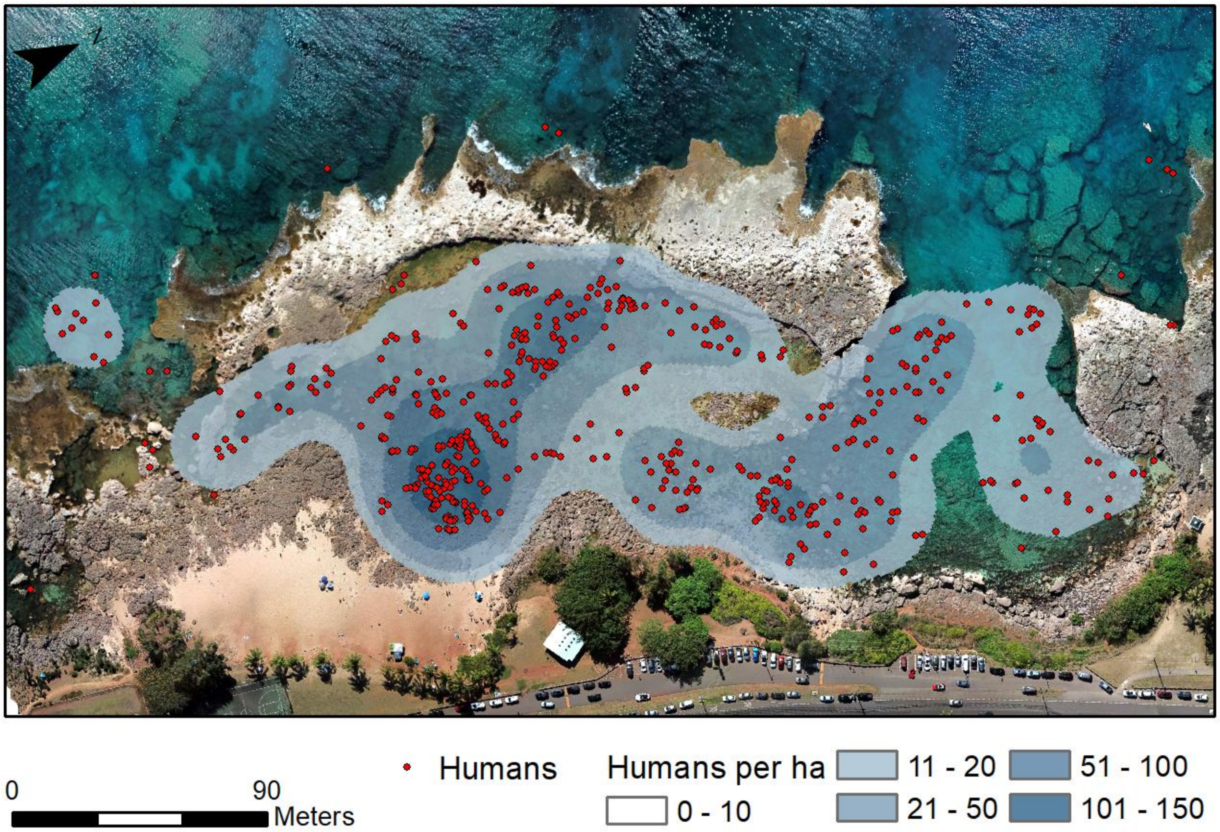


Figure 7. Locations of mapped humans from all UAV surveys combined overlaid on mean kernel density surface.

Visitor tracking

A total of 130 visitors were tracked engaging in snorkeling, wading, swimming, and SCUBA activities resulting in nearly 86 hours of observation time and covering over 33 km (Table 2). The average water time spent for each activity varied between 28 minutes for wading and 49 minutes for SCUBA. Likewise, the average distance covered ranged from 132 m for wading and 600 m for SCUBA (Table 2). A total of 1,471 substrate contacts were observed of which 25% were on algae (turf, CCA, macroalgae) and 5% were on corals. SCUBA divers had the highest average number of substrate contacts and coral contacts per dive, followed by snorkelers (Table 3). However, snorkelers had a much lower incidence of coral contact. Swimmers and waders had the highest average number of algae contacts per session and negligible contact with corals (Table 3). Five out of the seven SCUBA divers contacted coral. Of these, one contacted coral a total of 15 times, 8 times with a fin and 7 times by hand. This pattern indicates an inexperienced diver with poor buoyancy control. One of the remaining four divers contacted coral 3 times by hand. The remaining three divers contacted coral a total of 6 times by fin.

Table 2. Summary of visitor tracking effort and results

Activity type	Number of visitors tracked	Total observation time (h)	Total distance covered (km)*	Total substrate contacts observed**	Average duration (min)	Average distance (m)*
Snorkel	85	58.8	24.1	1170	41.5	359
Wade	23	10.8	3.0	24	28.2	132
Swim	15	10.5	3.3	172	41.9	236
SCUBA	7	5.7	2.9	105	48.7	599
Total:	**130**	**85.8**	**33.3**	**1,471**		

*based on 110 surveys
**only live substrate contacts recorded for waders

Table 3. Summary of average visitor substrate contacts per session

Activity type	All substrate contacts per session	Non-living	Algae	Coral
SCUBA	15.0	10.6	1.0	3.4
Snorkel	13.8	10.2	3.0	0.5
Swim	12.3	6.8	5.4	0.0
Wade*	1.04	0.0	5.0	0.04

*only live substrate contacts recorded

Spatial patterns of visitor usage were very similar to those shown by the UAV mapping and highly correlated to the two main access points for the Tidepool and Cove, respectively (Fig. 8). In the Tidepool, visitors frequented the sandy substrate and/or deeper areas so that high use areas were a well-defined subset of the overall area of the Tidepool. Substrate contacts were common throughout this high-use area and generally decreased in density with distance from the access point (Fig. 8). In contrast, visitors tended to roam throughout the entire area of the (inner) Cove, though the highest track density was around the access point and the southwest side. Likewise, substrate contacts in the Cove were primarily clustered around the access point (Fig. 8). Interestingly, the visitor tracking data omits the far south end of the tidepool which was represented in the UAV survey data. This is likely because observers primarily focused on the main access points to maximize survey numbers.

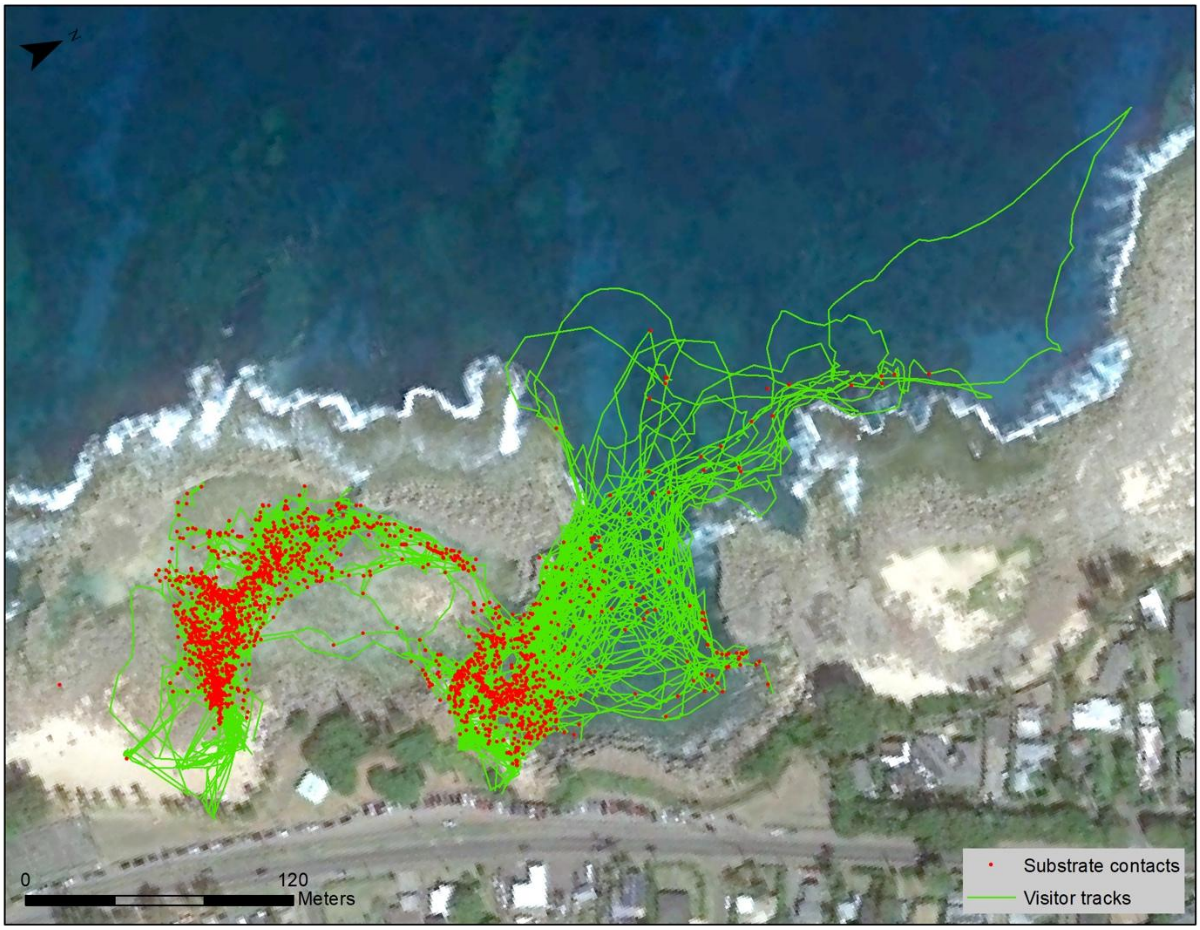


Figure 8. Spatial summary of visitor tracking data from August 20th to September 14th, 2022 showing visitor tracks and substrate contact points.

Usage tracks varied by activity type (Fig. 9). Snorkel is the most popular in-water activity and individuals ranged throughout the Tidepool and Cove, though the general patterns matched those described above (Fig. 9A). The SCUBA divers surveyed followed a consistent pattern setting out from the main entrance to the Cove and heading out and north before returning (Fig. 9B). One individual followed a similar but slightly different pattern by following the South wall of the Cove entrance before turning north when clear of the Cove mouth. Swimmers stayed in the deeper area in the center of the Tidepool and in the shallow areas of the Cove (Fig. 9C). Substrate contacts for all activities were focused in shallow water areas and near access points. Only SCUBA divers made substrate contact in deeper water given their proximity to the substrate, regardless of depth (Fig. 9B).

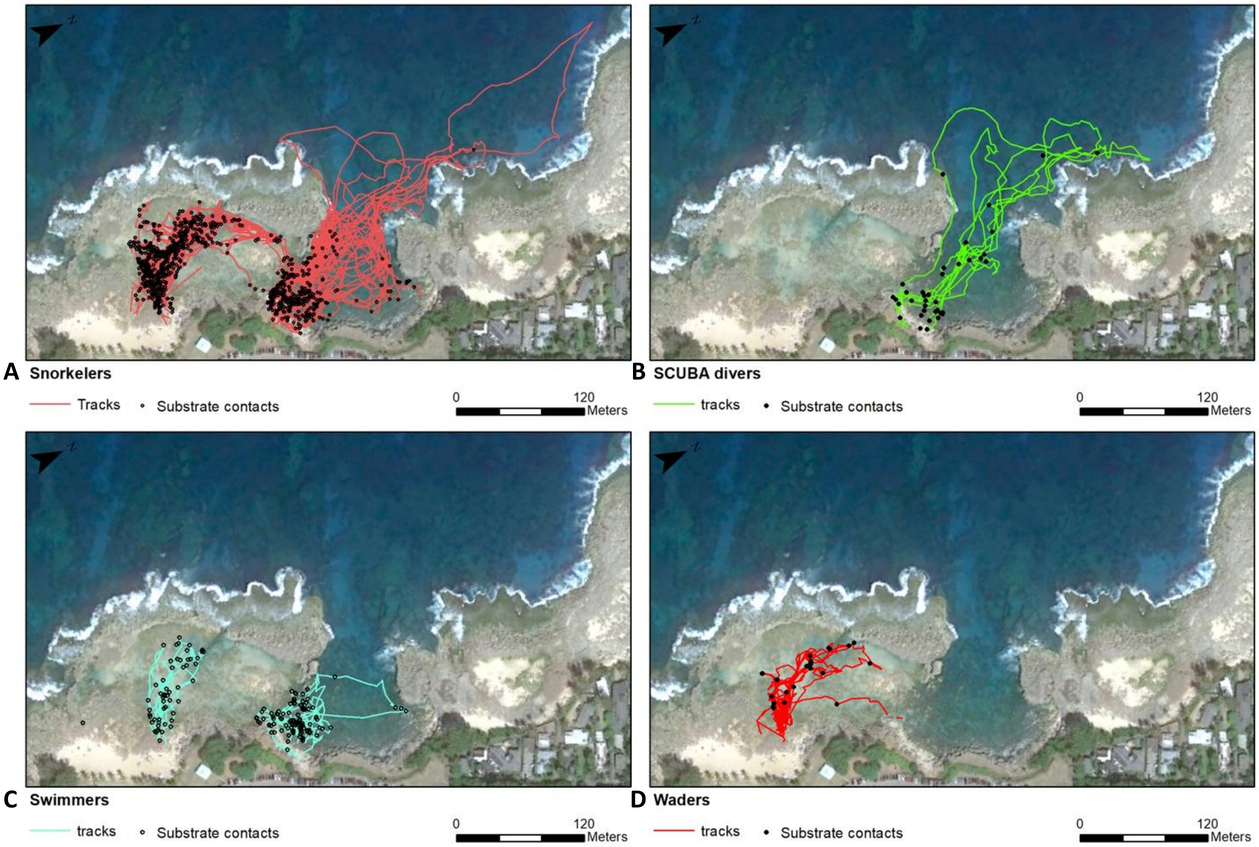


Figure 9. Spatial summary of visitor tracking data for A) snorkelers, B) SCUBA divers, C) Swimmers, and D) Waders. Substrate contacts shown for Waders only represent live substrates.

Marine life and human effects

Fishes

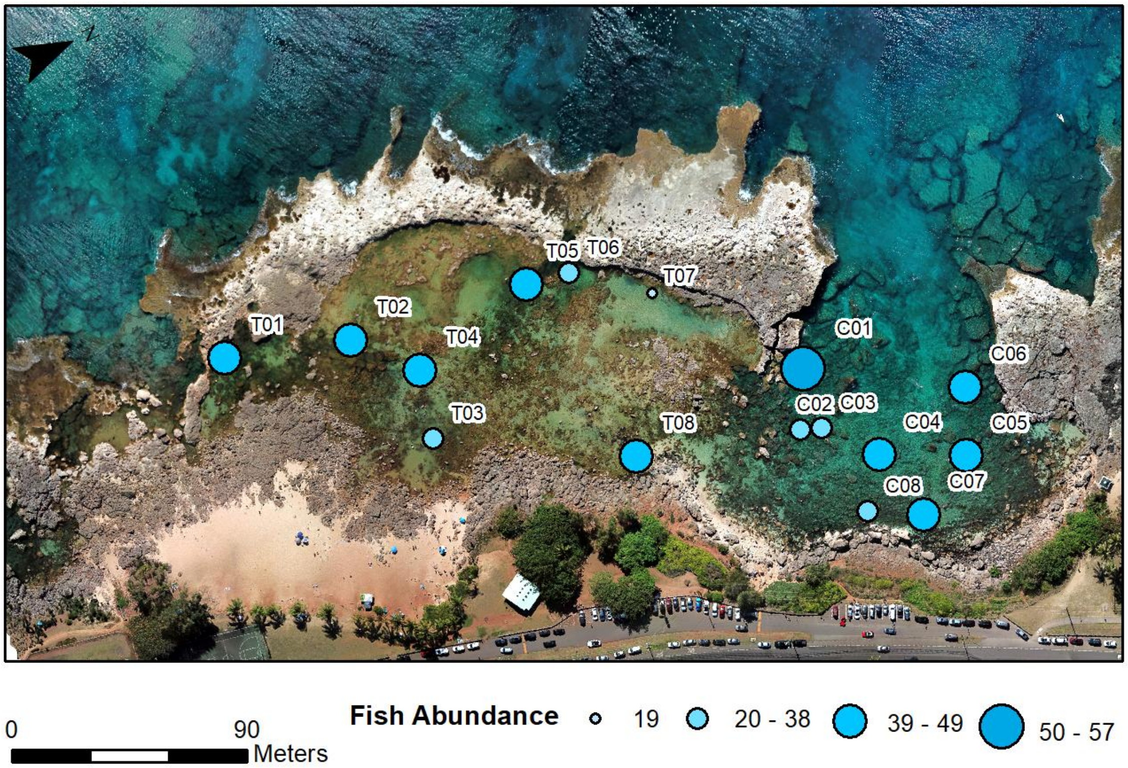
A total of 18 rounds (8 transects each) were completed in the Tidepool and 16 rounds (8 transects each) in the Cove between June and August 2022. Fish abundance ranged from five to over a hundred fish per survey. Fish richness ranged from four to twenty-four species per survey. Āholehole (*Kuhlia sandvicensis*) were the most abundant species found in the Tidepool with three times higher numbers on average compared to the Cove. Likewise, manini (*Acanthurus triostegus*) were nearly two times more abundant in the Tidepool, highlighting the importance of this habitat (Table 4). Other schooling species such as `iao (*Atherinomorus insularum*) and uouoa (*Neomyxus leuciscus*) were observed in similar numbers in both zones. The most abundant species observed were primarily herbivores or secondary consumers (invertivores, corallivores). See Jones (2022) for the full list of fish species recorded.

Table 4: Top ten species by number in the Tidepool and the Cove.

Tidepool		Cove	
Species	Mean abundance	Species	Mean abundance
Kuhlia sandvicensis	9.8	*Neomyxus leuciscus*	9.0
Atherinomorus insularum	8.9	*Atherinomorus insularum*	7.0
Acanthurus triostegus	8.0	*Acanthurus nigrofuscus*	6.9
Neomyxus leuciscus	7.4	*Acanthurus leucopareius*	6.6
Chromis vanderbilti	6.6	*Stethojulis balteata*	5.2
Acanthurus nigrofuscus	4.4	*Acanthurus triostegus*	3.9
Thalassoma duperrey	4.3	*Thalassoma duperrey*	3.7
Stethojulis balteata	4.1	*Stegastes fasciolatus*	3.4
Stegastes fasciolatus	3.7	*Kuhlia sandvicensis*	3.3
Abudefduf abdominalis	3.2	*Fistularia commersonii*	3.1

Average fish abundance was variable across transects with highest abundance at site C1 in the Cove (Fig. 10A). Site T7 in the Tidepool had the lowest abundance likely due to the lack of hard bottom habitat (Fig. 10A). Average fish richness was higher at the Cove sites compared to Tidepool sites (Fig. 10B). In the Tidepool, the highest fish richness was found at site T5.

A



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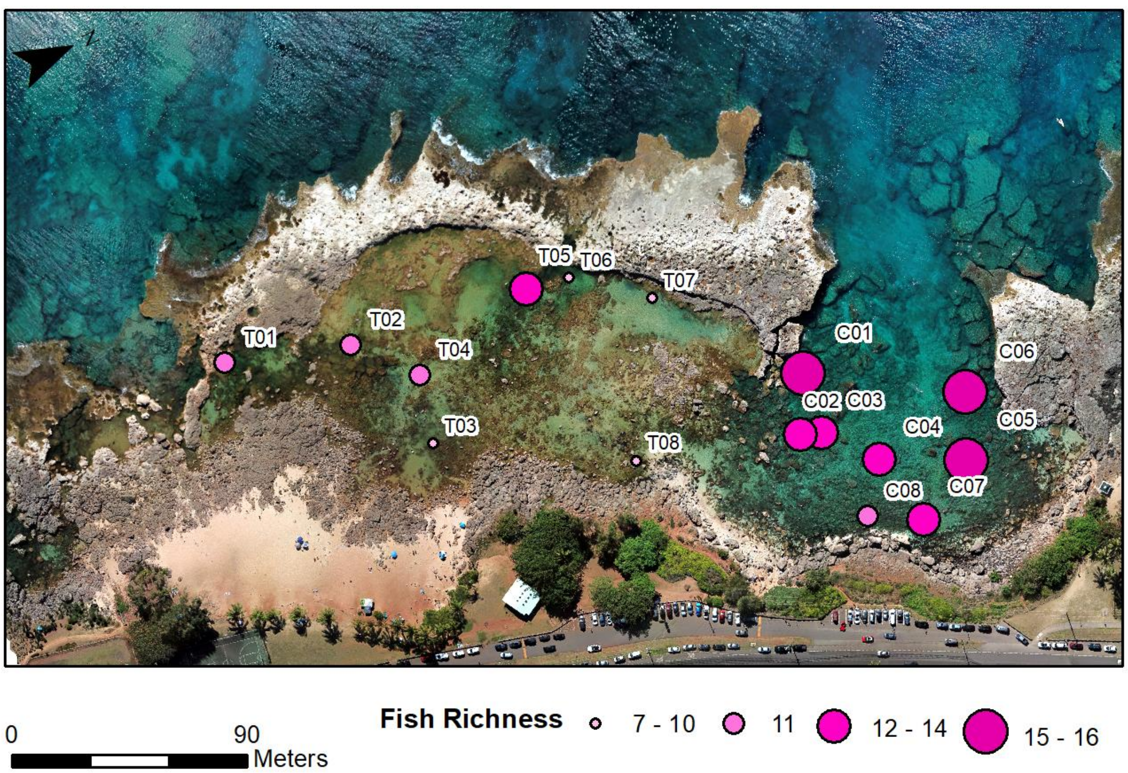

Figure 10. Mean A) fish abundance and B) fish richness per transect.

The following results focus on human effects on overall fish abundance, abundance of herbivorous fishes, and abundance of secondary consumers and overall species richness (number of species) at the transect level, with corresponding human use counts for standing or swimming humans within 10m of the transect center and standing or swimming humans on the transect itself.

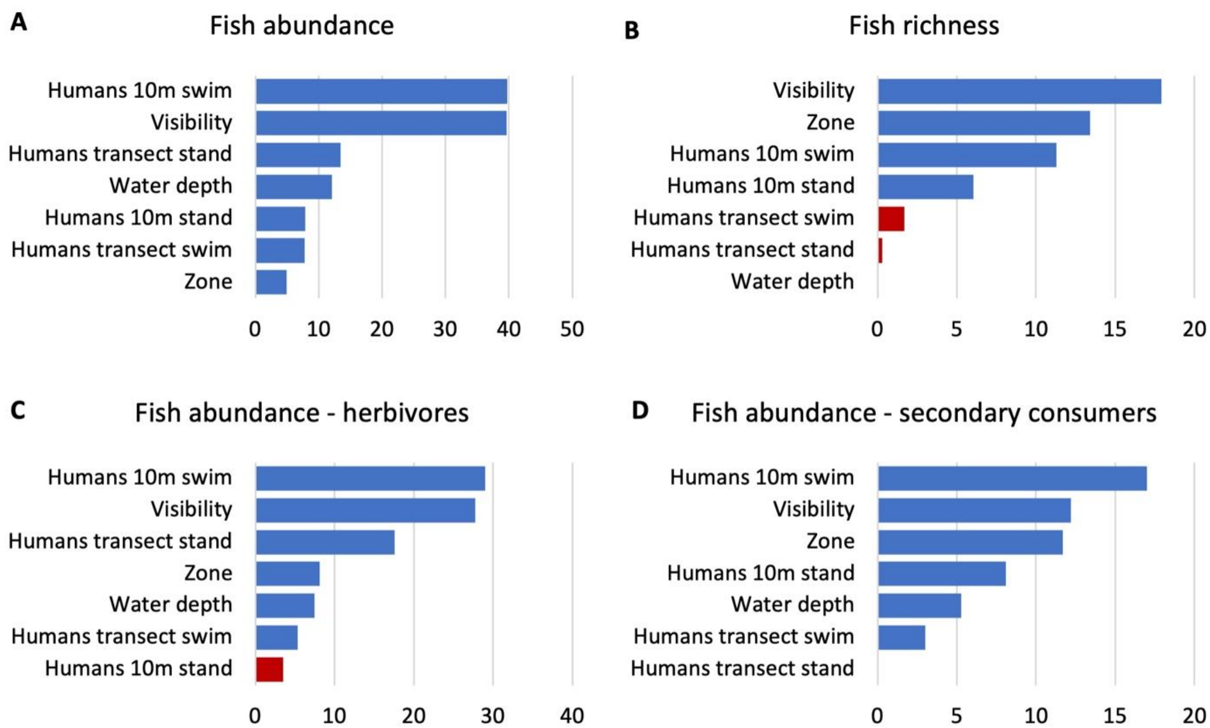

Figure 11. Variable comparison for LMMs of A) overall fish abundance, B) overall fish richness, C) herbivore abundance, and D) secondary consumer abundance. Variable scores (F value) shown in blue are significant ($p<0.05$) and scores shown in red are not significant ($p>0.1$).

For all measures of fish abundance, the number of humans swimming/floating within 10m of the transect was the most important predictor, followed by visibility or water clarity (Fig. 11A, C, D). For overall fish richness, visibility and zone were the most important factors, followed by humans swimming and standing within 10m (Fig. 11B).

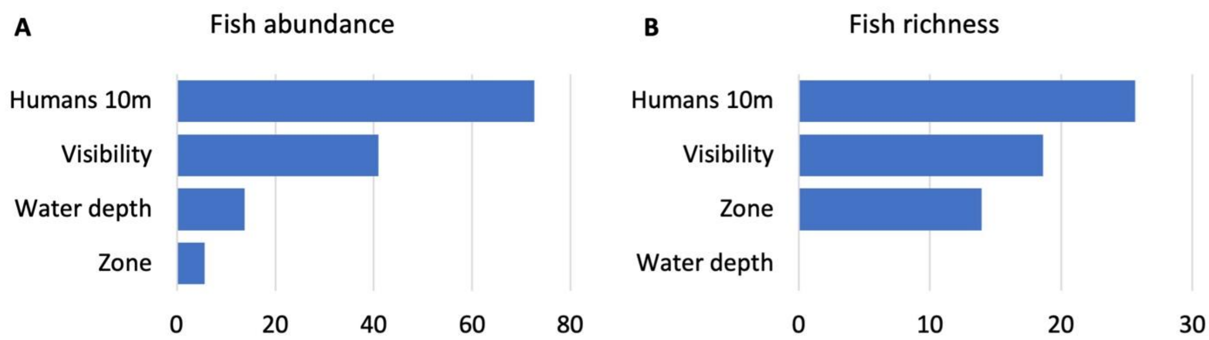

Figure 12. Variable comparison for LMM models of A) overall fish abundance, and B) overall fish richness with combined counts of humans within 10m. Variable scores (F value) shown in blue are significant (p<0.05) and scores shown in red are not significant (p>0.1).

When counts of humans (standing and swimming) within a 10m radius of the center of the transect were combined, it became the strongest predictor of both overall fish abundance and richness (Fig. 12A, B), as well as the abundance of herbivores and secondary consumers, respectively. Visibility and Zone were also significant predictors of both fish abundance and richness, while water depth only affected fish abundance (Fig. 12A, B). Fish abundance (Fig. 13A) and richness were both higher in the Cove compared to the Tidepool. Depth had a negative effect on fish abundance, so more fishes were observed in shallow water (Fig. 13B). Visibility had a positive effect on fish abundance (Fig. 13C) and richness, which is likely an effect of sampling. Finally, humans within a 10m radius of the transect had a strong negative effect on both fish abundance (Fig. 13D) and richness. There was no interaction between Zone and Humans for either model, meaning that human density had the same effect on abundance and richness in both the Tidepool and Cove.

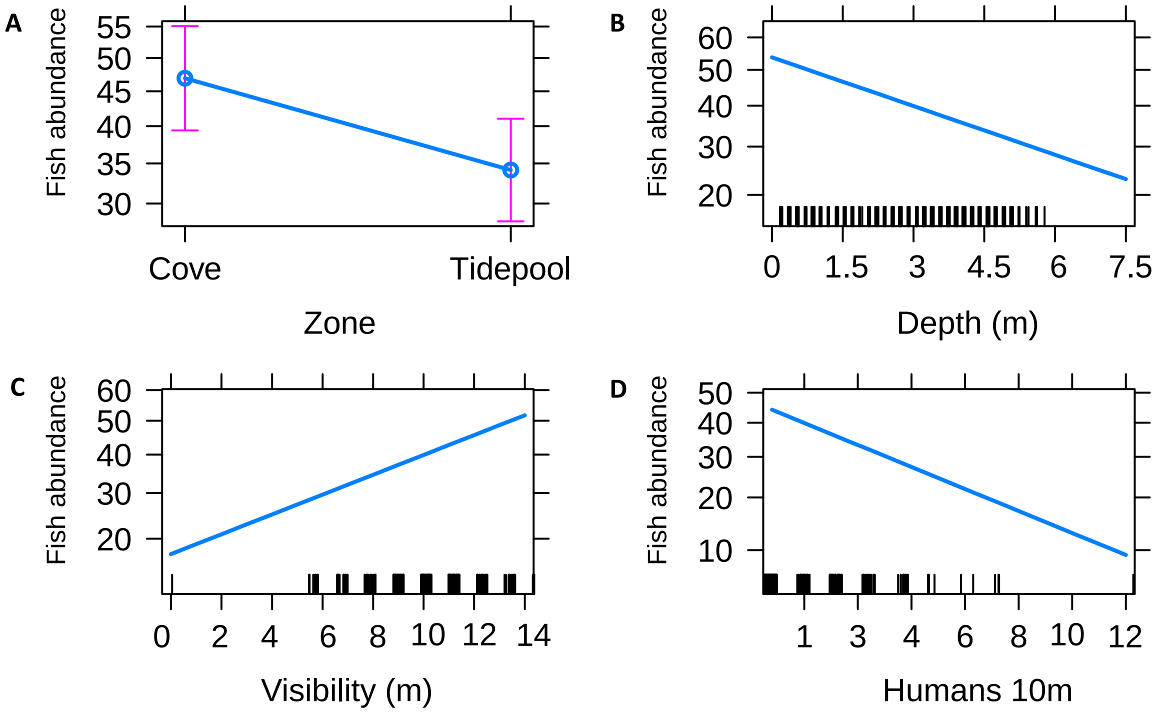

Figure 13. Linear mixed model (LMM) effects for fish abundance and combined counts of humans within 10m. A) Zone, B) depth, C) visibility/ water clarity, D) Humans within 10 m of the transect center

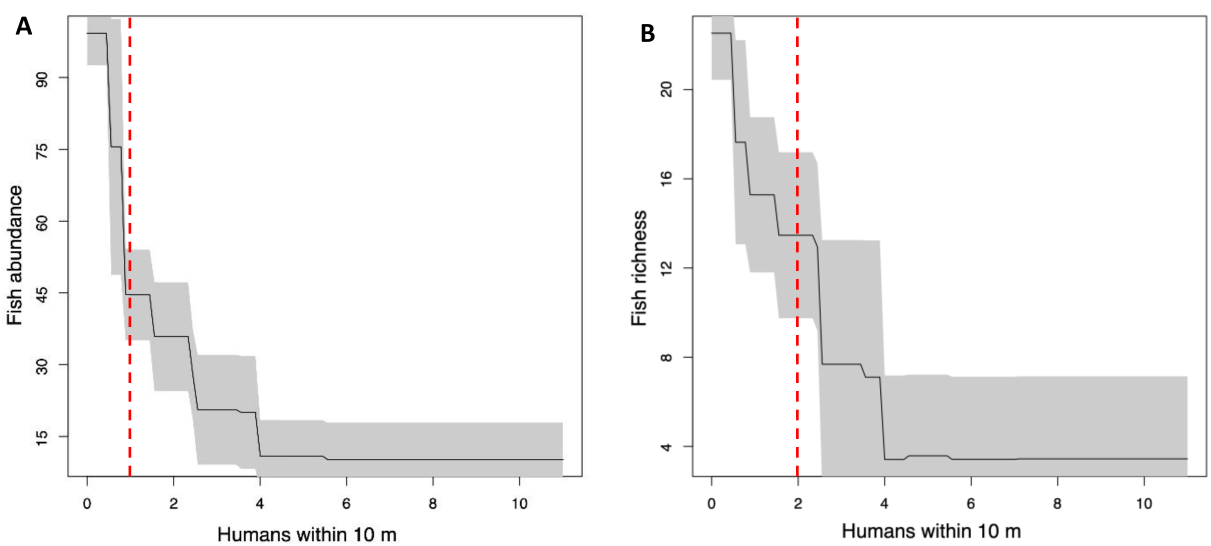

Figure 14. Partial dependence plots of human influence from BRT models of A) fish abundance and B) fish richness. Red lines denote thresholds in human density corresponding to steep declines in fish abundance and richness, respectively.

To explore potential thresholds of human densities on fish abundance and richness, BRT models were fit using the same variables as the linear mixed models presented above. The BRT models explained 48% and 50% of the variability in fish abundance and richness, respectively. Partial dependence plots of the number of humans within 10 m revealed apparent thresholds of one human per 314 m^2 (the area of a circle with a 10 m radius) for fish abundance (Fig. 14A) and two humans per 314 m^2 for fish richness (Fig. 14B). With four or more humans within 10 m, both fish abundance and species richness drop to minimal levels (Fig. 14).

Mobile invertebrates

Mobile invertebrates were counted on the same transects as the fishes. Mobile invertebrate abundance ranged from five to 135 and species richness ranged from one to seven species per transect. The majority of mobile invertebrates observed were rock-boring urchins of the family Echinometridae, averaging 20 per transect in the Cove and 30 per transect in the Tidepool. All other mobile invertebrate groups averaged less than two per transect and included crabs, other urchin species, and sea cucumbers. See Jones (2022) for the full list of mobile invertebrate species. The highest abundance of mobile invertebrates (rock-boring urchins) was observed in the Tidepool at site T5, with several other sites also showing high abundance (Fig. 15). In the Cove, the highest abundances were observed at the northern sites C5 and C8 (Fig. 15).

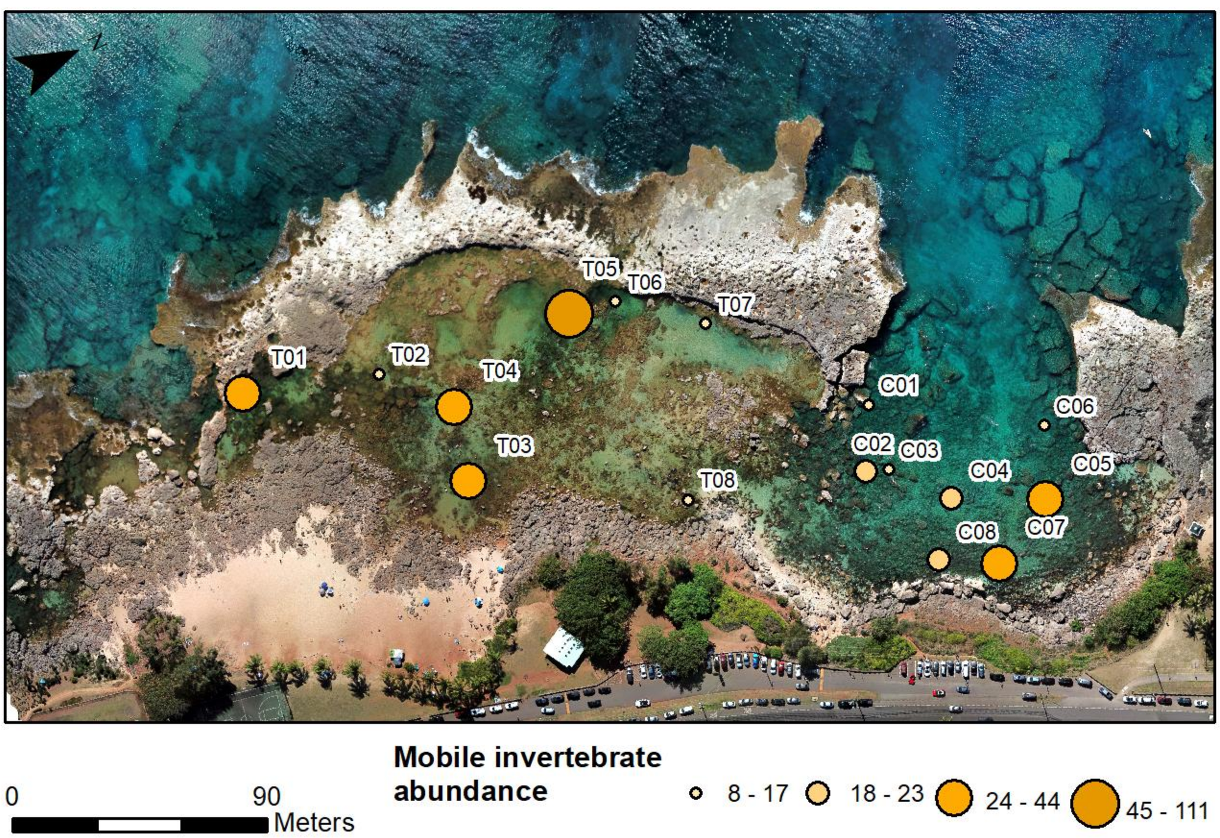

Figure 15. Mean mobile invertebrate abundance by transect.

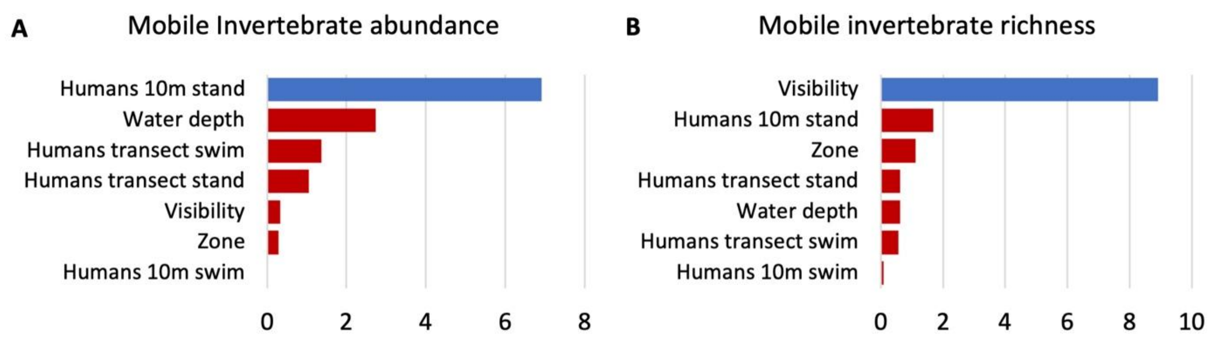

Figure 16. Variable comparison for LMM models of A) mobile invertebrate abundance, and B) mobile invertebrate richness. Variable scores (F value) shown in blue are significant at a level of 0.05 and scores shown in red are not significant.

This analysis focuses on human effects on mobile invertebrate abundance and species richness (number of species) with corresponding human use counts for standing or swimming humans within 10m of the transect center and standing or swimming humans on the transect itself. Mobile invertebrate abundance was influenced by humans standing within 10 m of the transect, none of the other measured variables were significant predictors (Fig. 16A). Mobile invertebrate species richness was influenced by water visibility and other variables including humans were not significant predictors (Fig. 16B). When counts of humans (standing and swimming) within a 10m radius of the center of the transect were combined, there was no significant relationship with mobile invertebrate abundance or richness.

Coral and Algae

Transect surveys

A total of three rounds of benthic cover surveys were conducted on the same transects as the fish and mobile invert surveys in July, August, and September 2022. The predominant living benthic cover on all transects was turf algae, followed by crustose coralline algae (CCA). CCA was more common in the Cove compared to the Tidepool. See Jones (2022) for a list of algae species recorded. Ten coral species from five families were identified on the transects (Table 4). Live coral cover was found on most transects though in relatively small proportions, except for the two transects along the northern edge of the tidepool (Fig. 17). Sessile invertebrates were mainly represented by Hawaiian blue octocoral (*Sarcothelia edmondsoni*), but also including some sponges (Porifera) and Zoanthids, were common in the Cove but nearly absent in the Tidepool.

Table 4. Coral species observed on Kapoʻo transects listed in order of mean percent cover.

Family	Species	Avg % Cover
Acroporidae	*Montipora capitata*	3.2
Agariciidae	*Gardineroseris planulata*	2.2
Poritidae	*Porites lobata*	2.0

Acroporidae	*Montipora patula*	2.0
Agariciidae	*Pavona varians*	2.0
Pocilloporidae	*Pocillopora meandrina*	1.4
Faviidae	*Leptastrea purpurea*	1.0
Acroporidae	*Montipora flabellata*	0.9
Poritidae	*Porites evermanni*	0.9
Pocilloporidae	*Pocillopora damicornis*	0.7

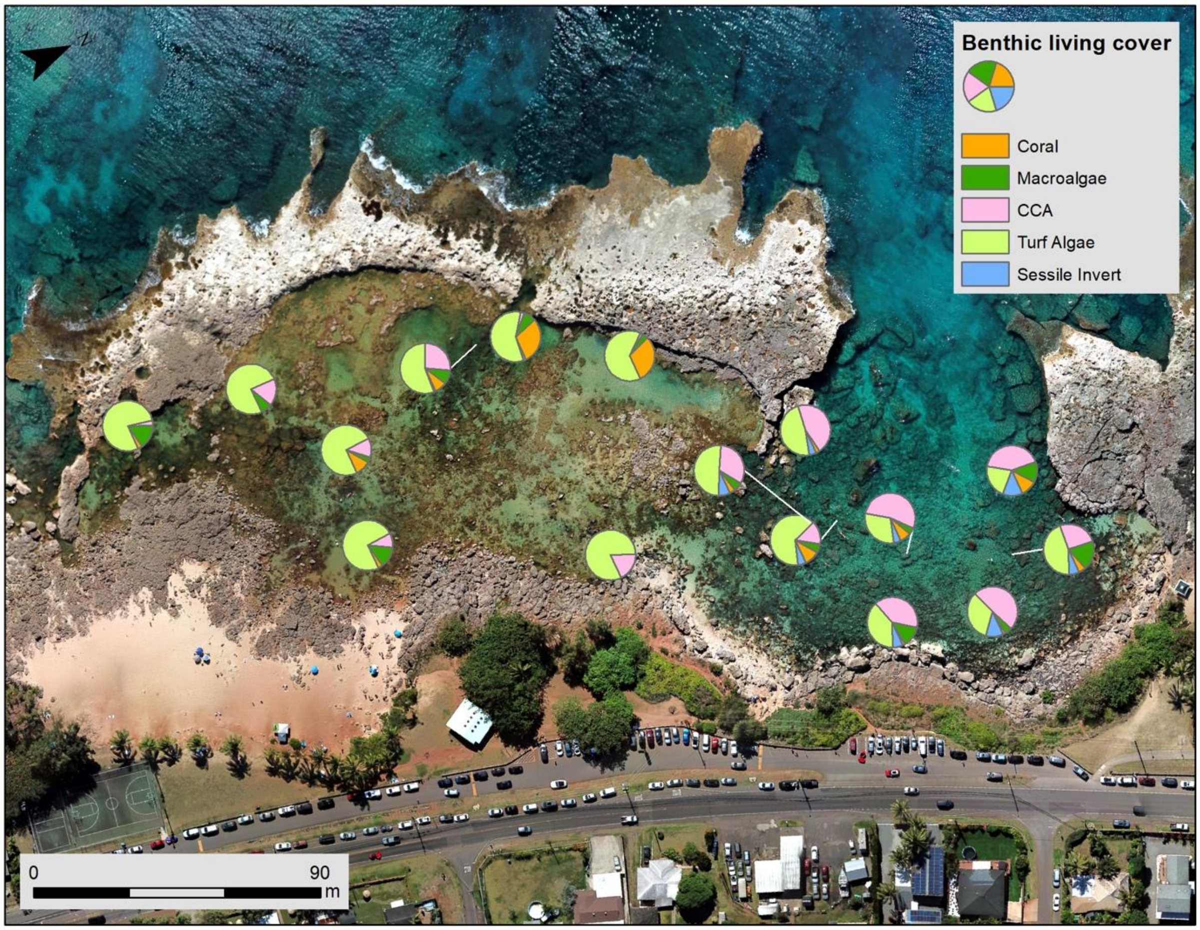

Figure 17. Benthic living cover as a proportion of each transect.

Transect measurements of Coral, Macroalgae, and Sessile invertebrate cover were compared with spatial patterns of human densities from the UAV surveys along with study zone and depth. Coral cover did not differ significantly between zones and human density was not a significant predictor of coral cover, though deeper areas had higher coral cover ($p<0.05$). Macroalgae cover did not have significant relationships with any of the variables tested. Sessile invertebrate cover was significantly higher in the Cove and showed a positive relationship with human density ($p<0.1$). It is unclear whether this is causative or correlative.

Roving coral survey

A total of 444 coral colonies representing 12 species were mapped of which 405 (91%) were at least partially living. Half of all corals surveyed were *Pocillopora meandrina* and the remainder (in order of abundance) were *Montipora capitata*, *Porites lobata*, *Pavona varians*, *Porites evermanni*, *Montipora patula*, with the remaining six species represented by five or fewer colonies. The depth of surveyed corals ranged from 0.2 – 3.7m. Corals greater or equal to 10cm in diameter (longest axis) were documented so that coral size ranged from 10 – 100cm with an average of 27cm. Coral damage was categorized into three types (breaks, scrapes, and "scrubs" – dead patches covered w/ turf, Fig. 18). Out of all corals surveyed, 292 (66%) were found to be damaged. Of these, the majority (59%) were scrubs, followed by scrapes (26%), and breaks (15%). Individual areas of broken coral were 9.9 cm on average (range 5-30cm), coral scrapes averaged 8.8cm (range 5-35cm), and scrubs were 11.2 cm on average (range 5-70 cm).

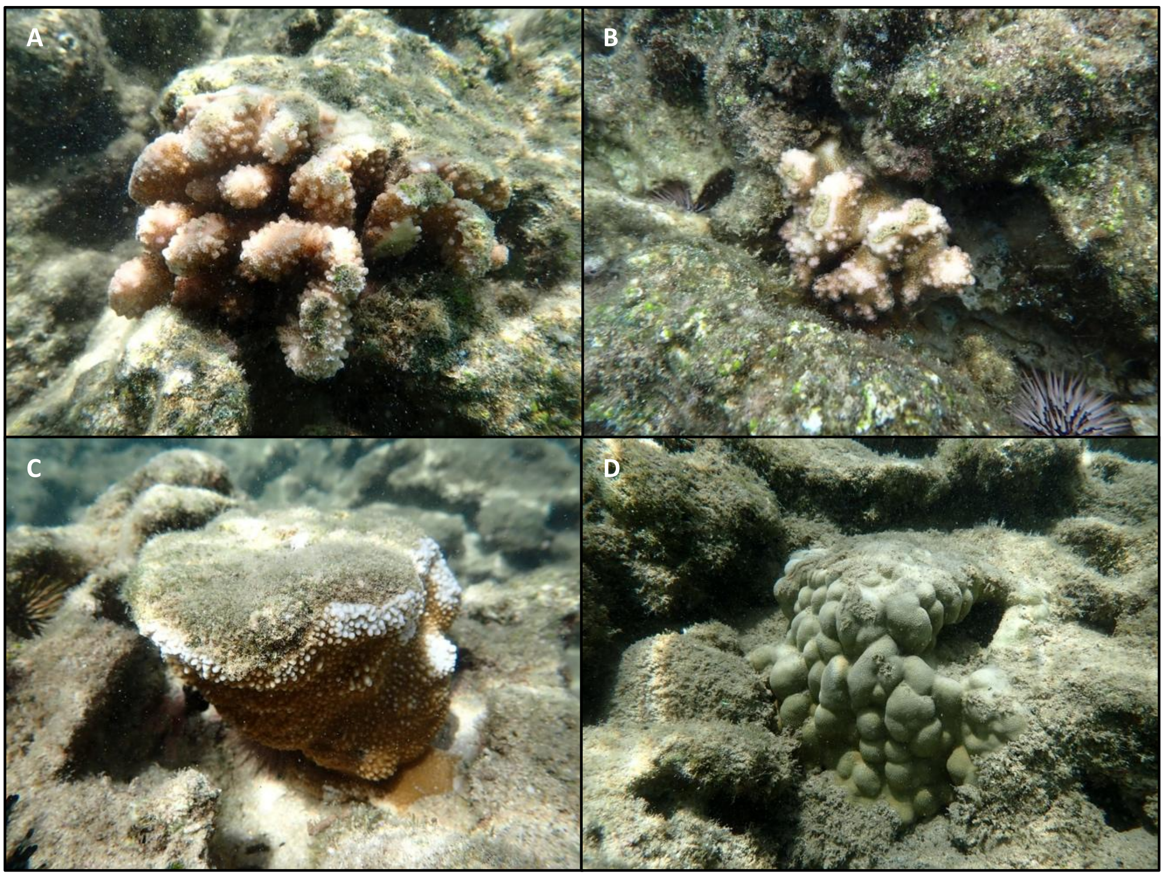

Figure 18. Examples of coral damage likely due to human trampling. A) Broken branches and tissue loss *P. meandrina*, B) broken branches *P. damicornis*, C) death and algae growth on top surface *M. capitata*, and D) death and algae growth on top surface *P. evermanni*. Photo credit: Ellie Jones.

Coral colonies in the southernmost area of the Tidepool were all living, while coral colonies in the central Tidepool and Cove were a mix of living, half alive, and dead (Fig. 19). Coral damage was documented throughout the surveyed area with higher occurrence appearing to correspond with primary access areas of the Tidepool and Cove, respectively, that also correspond to high traffic/use areas (Fig. 20).

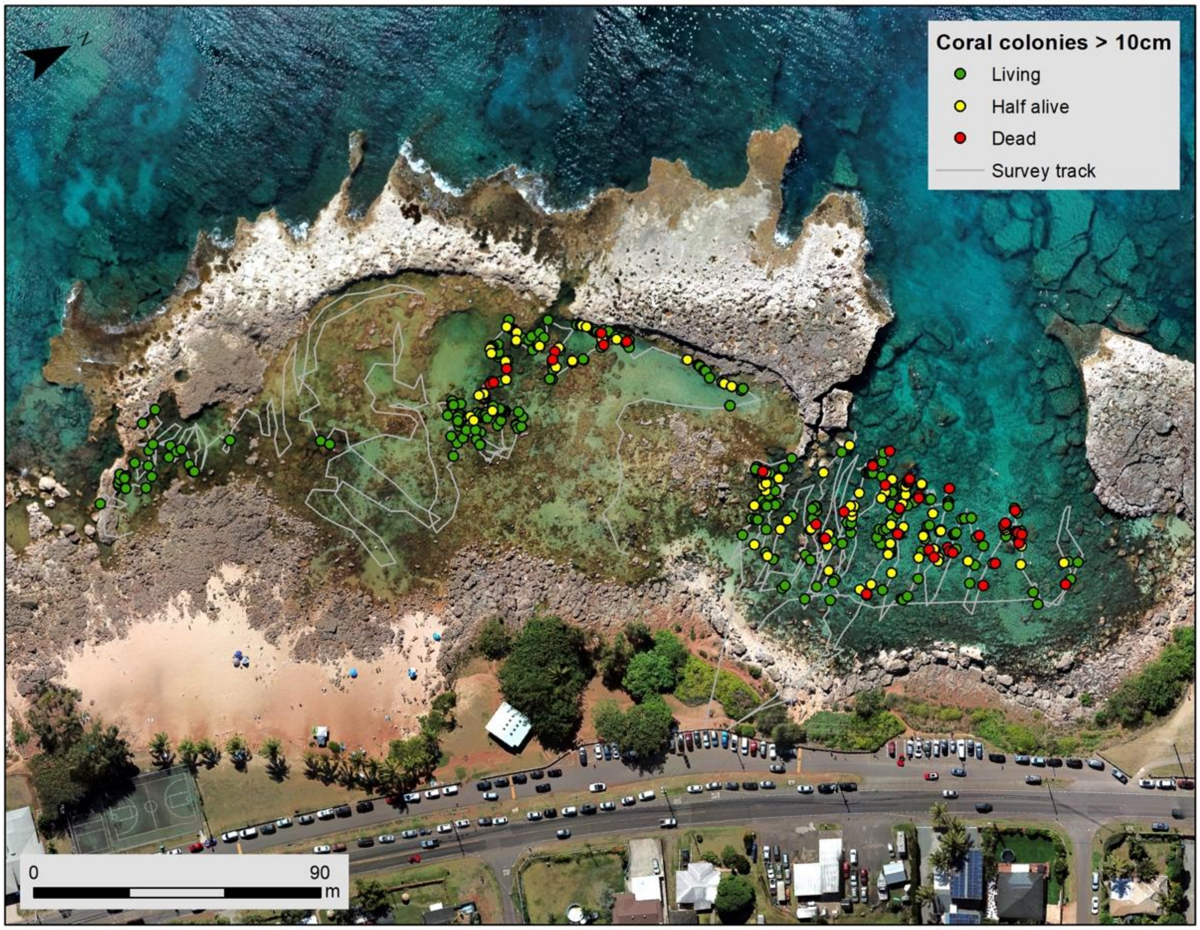

Figure 19. Summary of coral status from the roving surveys.

The binomial logistic regression model revealed a significant positive effect of human density on the probability of coral damage ($p<0.001$). For areas with the lowest human densities, the probability of a coral being damaged was ~50%, for areas with the highest human densities the probability of damage increased to over 80% (Fig. 21A). Depth was also a significant predictor of coral damage ($p<0.1$) with shallower corals having a higher probability of damage (Fig. 21B). However, depth explained a great deal less of the variability compared to human density. Coral species and coral size were not significant predictors of damage and were not included in the final model.

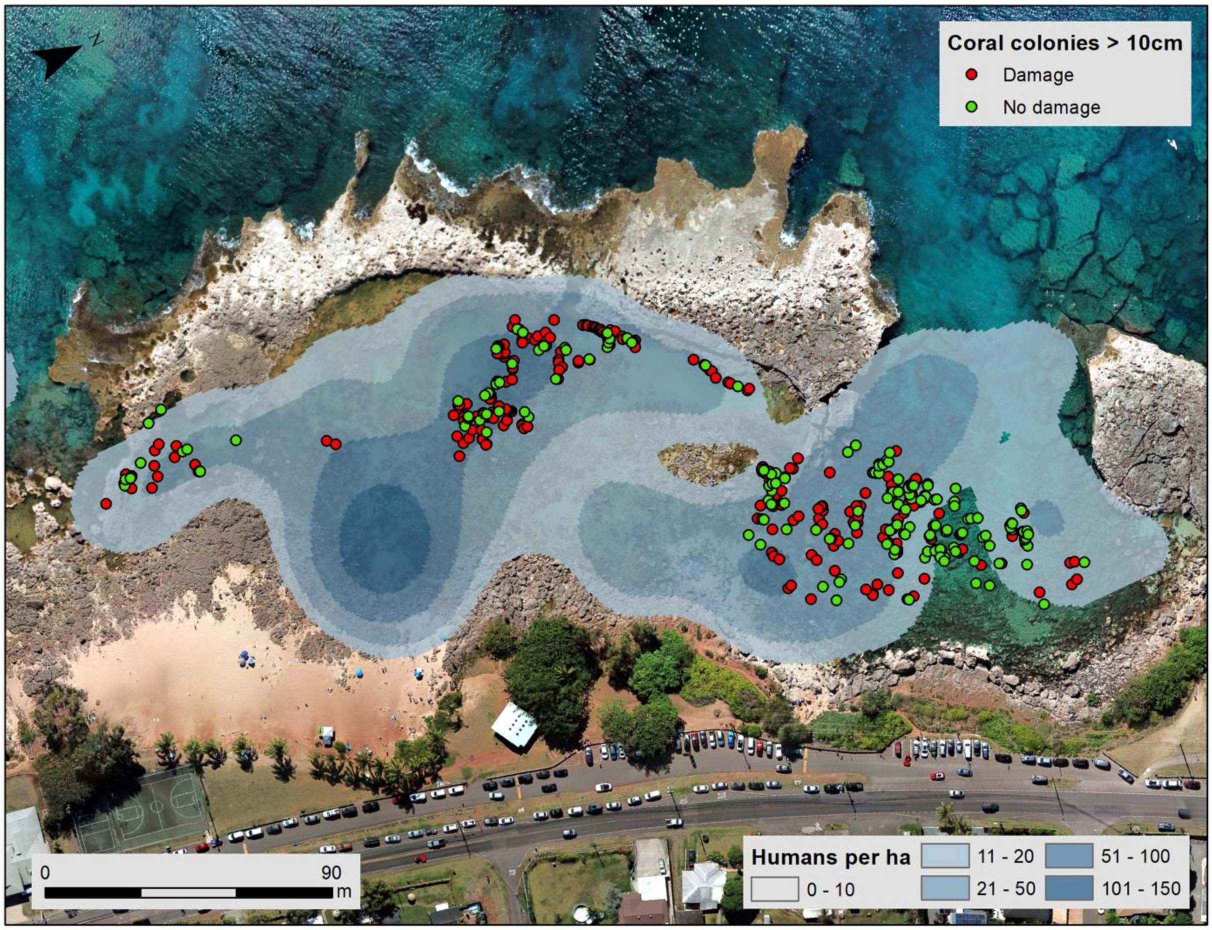

Figure 20. Summary of coral damage from the roving survey overlaid on human density from UAV surveys.

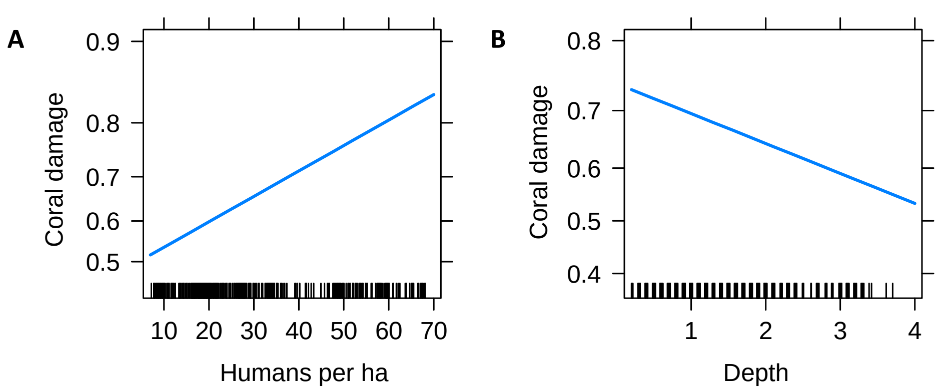

Figure 21. Effect plots from the binomial logistic regression model testing incidence of coral damage vs A) human density and B) depth.

Carrying capacity

The results of this study clearly show the effects of human presence on fish abundance and species richness, as well as coral health. Thresholds of human density upon which management actions could be based were identified for the fish indicators. Fish abundance was more sensitive to human presence than fish richness, though both showed a large decrease when there was a human within a 10 m radius (Fig. 14). This is equivalent to one human per 314 m^2 (the area of a circle with a 10 m radius) or 31.8 humans per hectare (ha – equivalent to 2.5 acres). This human density threshold was applied to different zone area estimates (Fig. 22) to derive a range of biological carrying capacity values for each study zone.

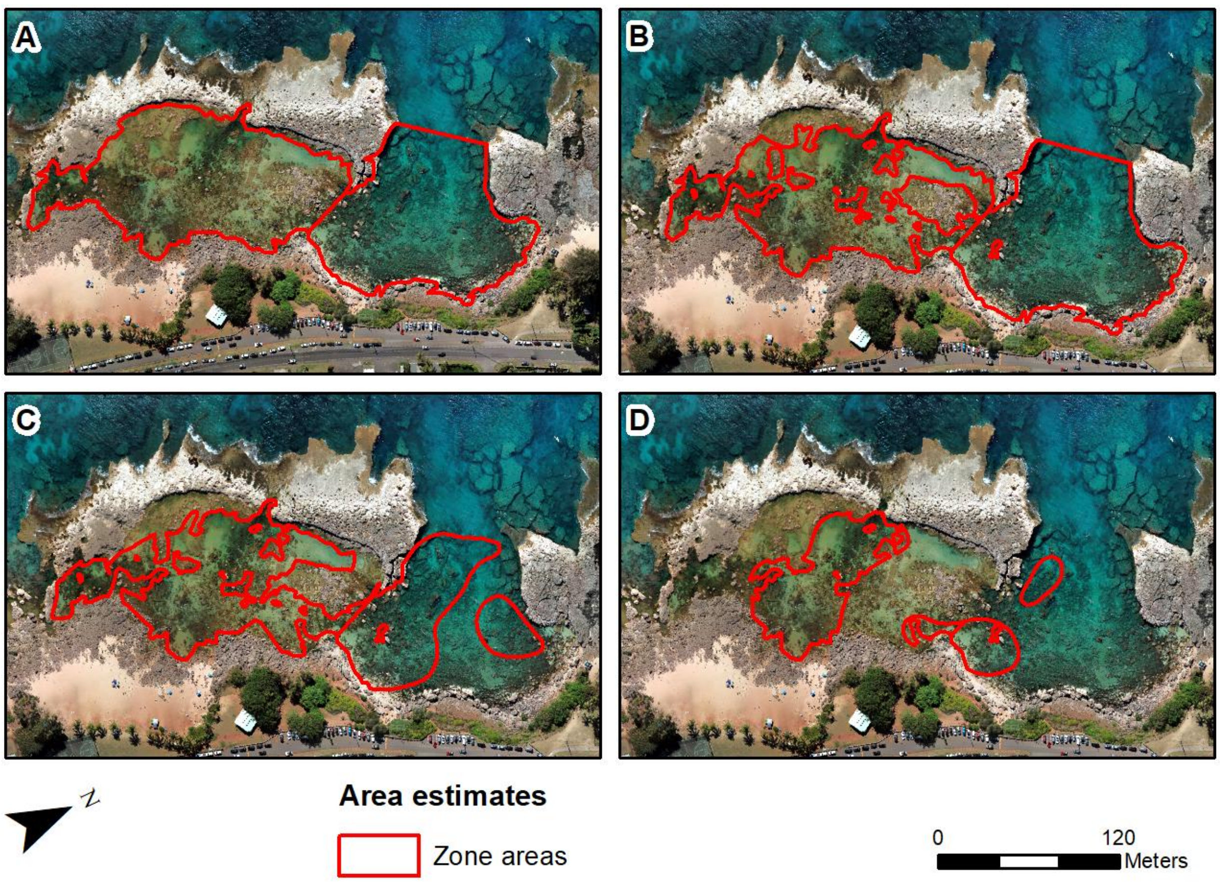

Figure 22. Maps of area estimates for the Kapoʻo Tidepools and Cove. A) Total area, B) low tide area, C) human majority, and D) humans high-density. See Table 5 for area values.

Based on these area estimates and the human density threshold for fishes, biological carrying capacity estimates range from 15 – 41 for the Tidepool and 5 – 35 for the Cove (Table 5).

Table 5. Descriptions of Kapo’o Zone area estimates with area in hectares (ha) and estimates of biological carrying capacity in number of humans.

Area calculation	Description	Tidepool area (ha)	Cove area (ha)	Tidepool capacity (humans)	Cove capacity (humans)
Total area	Total area	1.28	1.09	41	35
Low tide area	Total area minus dry rocks at low tide	0.98	1.08	31	34
Humans - majority	Area of where 90% of humans were found	0.89	0.6	28	19
Humans - high density	Area where > 32 human/ha were found	0.46	0.16	15	5

Discussion

Human usage of Kapoʻo

The MPW visitor count data provides the best source from which to estimate temporal usage patterns by zone. The hourly analysis clearly shows peak in-water visitation in the afternoons with most of the use occurring in the Tidepool. Daily use patterns were variable though also showed most of the use occurring in the Tidepool. The data show Thursday as the highest use day, however, this is based on an average of just three surveys so additional data is needed to confirm. The monthly data shows an obvious shift of human use from the Tidepool to the Cove over the transition from winter to summer. As a result, the Tidepools have their highest levels of use in March and April reaching over 80 people in the water at one time. This is related to the seasonal wave regime which restricts usage of the Cove during high winter surf, displacing humans to the Tidepool as one of the few options for swimming/ snorkeling not just at Kapoʻo but on the entire north shore of Oʻahu. In-water human use numbers between Tidepool and Cove start to even out beginning in June and persist at high levels through at least September.

Spatial patterns of visitor use of Kapoʻo were fairly consistent based on both UAV mapping and tourist tracking datasets. Use patterns were oriented primarily to the main access points and the area of highest human density was in the center of the Tidepool stretching between the shoreward access point and the crack at the seaward margin. The area with the next highest human density was the primary access to the Cove and with high density levels extending north along the edge of the west edge of the Cove and west into the Tidepool.

Patterns in dive duration for snorkelers and SCUBA divers generally correspond to those found by Meyer and Holland (2008) in their visitor tracking study of four Hawaiian MPAs including Pūpūkea. SCUBA divers surveyed in this study had mean dive times of 49 min vs. 60 min in the prior study and snorkelers had mean dive times of 42 min vs 30 min. Patterns in visitor substrate contacts generally follow similar patterns as described above though are constrained by depth in the Cove with far fewer contacts in deeper water. Mean substrate contacts per dive were 50% higher for SCUBA and nearly 300% higher for snorkelers compared to Meyer and Holland (2008). This could be because all visitors in this study originated from shore whereas boat divers were also included in the earlier study. Overall, the majority of substrate contacts in this study were on non-living substrates and most living substrates contacted were algae rather than coral. While the present study included two additional use types (swimming and wading) not included in Meyer and Holland (2008), several of the general findings are the same: 1) recreation impacts on coral reef habitats were generally low, 2) SCUBA divers had greater impacts per dive than snorkelers (or other use types), and 3) individual behavior largely determined level of impact.

Human effects on marine life

Of all marine species included in this study, fishes showed the most direct and obvious response to human presence. Human density was the most important predictor of fish abundance and richness for all fish response variables tested. Aside from differences between Zones (fish abundance and richness were higher in the Cove) water clarity and depth were also key predictors. For this study, water clarity was negatively related to human density. Water clarity influences measurement, the ability of the observer to see and count fishes (Figueroa-Pico et al. 2020), though it may also have an ecological effect. Previous research has shown that turbidity impairs habitat choice (Wenger et al. 2011), foraging, growth, and condition (Wenger et al. 2012, Johansen and Jones 2013) of coral reef damselfish.

In contrast to fishes, mobile invertebrates did not show an effect from human presence other than a weak but significant effect on abundance from humans standing within 10m. However, when human counts (swimmers and standers) at 10m were combined, there was no longer a significant relationship. The vast majority (90% in the Cove and 93% in the Tidepool) of mobile invertebrates counted were rock-boring urchins (Echinometridae). These robust species have evolved to live in high-wave impact zones and spend the day in burrows coming out at night to feed (Satyawan et al. 2013). For these reasons, they are well adapted to human trampling impacts. The positive signal for humans standing likely came from the small non-Echinometridae component of observed species – other urchins, crabs, and sea cucumbers. Unfortunately, there was not enough data to test them separately.

Transect-based measurements of coral, macroalgae, and sessile invertebrates did not show any link with human density, apart from a weak positive relationship with sessile invertebrates. For coral, this could be because human trampling impacts are localized and would not affect overall cover estimates, especially at the transect scale. The same could be true for macroalgae and since macroalgae tend to have a fast growth rate, any trampling impacts would be temporary. The (non-coral) sessile invertebrates were mainly composed of Hawaiian blue octocoral (*S. edmondsoni*). The positive relationship with human density shown here is likely a coincidence, unless it is an attraction for snorkelers, though additional research would be needed to confirm this.

The roving coral impact survey was dedicated specifically to mapping and documenting the impact on corals and the occurrence of coral damage showed a strong positive relationship with human density. Several types of damage were recorded, and initial models focused just on recent damage (breaks and scrapes) where coral skeletons were exposed. These models did not show a relationship with human density. Given the low rate of coral contact recorded with the visitor tracking, older injuries (now covered in turf algae) were subsequently included in the models resulting in a positive relationship. Vermeij et al. (2010) demonstrated a growth rate of 0.1 mm/wk for turf algae under elevated nutrients. Under these conditions, coral damage that occurred at the beginning of the summer season in mid-April could be completely overgrown by turf algae by mid-September (20 weeks later). In addition, shallower corals were more susceptible to damage consistent with human trampling, as well as elevated water temperatures that could lead to partial bleaching and mortality. Walker et al. (2020) demonstrated that surface water temperature patterns in the Kapoʻo Tidepool were highly variable and dependent on tide and rainfall. Even so, with the data collected in this study it is not possible to separate partial mortality due to human trampling vs. bleaching though the results make a strong case for the former.

Management implications

The visitor count data identifies periods of high usage upon which management actions should focus. The first is February through May before the north swells have subsided and human use is focused in the Tidepool resulting in the highest numbers of the year. The remainder of the summer through at least September shows similarly high overall use levels though spread between the Cove and Tidepool. Presumably, during the rest of the year usage levels are relatively low though this should be confirmed with year-round visitor counts.
At a daily scale, the afternoon hours 12pm – 3pm see the highest visitor counts which should also be a focus for management.

The results of this study clearly show the effects of human presence on fish abundance and species richness, and the probability of coral damage. Thresholds of human density upon which management actions might be based were identified for the fish indicators and used to calculate biological carrying capacity based on a range of area estimates. By providing a range, it allows for managers to make the final decision on the level of acceptable risk. Two of the area estimates are based on human density as mapped in this study, the area with most humans and the area with the highest human density. Selecting a lower carrying capacity estimate corresponding with one of these areas would help protect the most visited and, therefore, most vulnerable areas of Kapo'o and retain these habitats for fish usage. Alternatively, selecting one of the higher carrying capacity estimates may reflect a decision to allow for a higher level of impact in these areas in favor of increased usage. Naturally, managers may choose to select any value of carrying capacity within the range provided.

The human counts (Summer 2022) in both the Tidepool and Cove were approximately 30 in-water visitors during the morning hours before noon. From 12pm to 3pm, these visitor numbers nearly double. To maintain a selected level of carrying capacity, managers may decide to focus on restricting in-water usage during the afternoon hours especially during February-May when in-water use of the Tidepool peaks.

The findings of this study are specific to Kapo'o and directly based on the data collected there. However, any implementation of use limits must be combined with continued monitoring to assess effectiveness and adapt as needed. The visitor tracking component showed that the level of impact is highly dependent on individual behavior which is likely equally important as the overall number of visitors. Any management actions to limit use should be accompanied with education such as rules or guidelines for visitors to avoid stepping on live coral, etc.

Directions for future research

Focus on research activities that inform management actions

This study employed a variety of methods, and several turned out to be more informative for management than others:

- *Fish and human monitoring using transects established in this study.* The estimates of biological carrying capacity determined here were based on the data from these paired surveys. By using the same transects, it enables monitoring of change over time.
- *UAV surveys of human-use.* This method yielded valuable data and was highly cost-effective. These surveys should be replicated in the winter months to compare patterns of use with the advantage that they are not dependent on sea conditions. It is possible that intensity of human use in the Tidepool is higher during the winter when visitors seek out this area that is protected from waves.
- *Coral damage surveys.* This targeted method is effective at quantifying and mapping coral impacts. This survey method could be improved by using a structured search pattern and diagnosing coral damage as human vs. bleaching induced mortality. When the data was compared to UAV maps of human use, it showed a relationship between coral damage and human density. Together, these data can be used to explore human density thresholds in terms of coral damage.

Conduct regular human-use counts over the entire year

There is a long time-series of human use data collected by MPW in the summer months that has documented patterns over time within different areas of the Pūpūkea MLCD. This program should be expanded to the winter months as well to document changing use patterns. Winter waves may cause non-surfing visitors to frequent the Tidepool area in search of protected waters. As suggested above, these surveys could be complemented with UAV surveys to reveal fine-scale spatial patterns of use within the Tidepool.

Expand study to consider other areas of the MLCD

While Kapo'o is recognized to be the most intensively used area of Pūpūkea MLCD, Three tables also has an abundant number of visitors to its shallow and vulnerable coral reef habitats. This would be the next logical area to study biological carrying capacity using the methods pioneered in this study. Another area of potential interest is the deeper areas seaward of the Kapo'o and Three tables. While human use is generally much lower here compared to the shallow areas, there are tour boats that bring visitors for snorkeling and SCUBA diving in these areas. Documenting impacts from SCUBA divers could be a study focus as they were shown to have the highest rate of live coral contact of any user group. Finally, the Kapo'o area includes an abundance of intertidal habitat that is also frequented by visitors. The MPW human-use surveys document users in these areas but levels of impacts are currently unknown.

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Appendix 1 – Biological survey protocols

Site and transect locations

Transects surveyed in this study were located within the Kapoʻo Tidepool and Cove of the Pūpūkea Marine Life Conservation District on the north shore of Oʻahu (Figure A1, Table A1). Transects were selected in locations that have greater than 50% hard bottom habitat, in approximately 1-3 m depth of water, in highly visited portions of the Tidepools and Cove. For Tidepool transects T6 and T7, the hard bottom is on the seaward side of the transect and the landward side of the transect is primarily sand. For these transects, only the seaward side was surveyed for benthic quadrats though the entire transect area was surveyed for fish and mobile invertebrates.

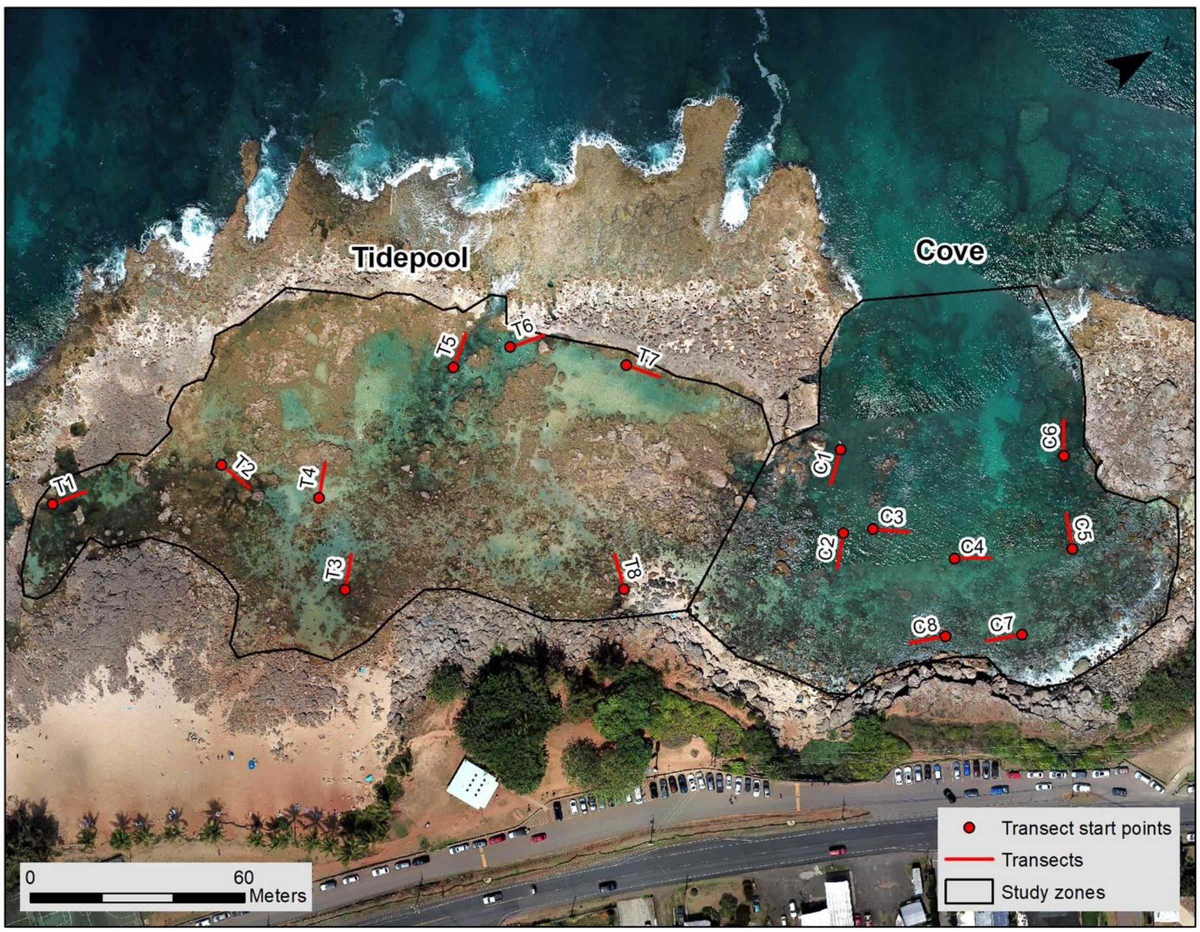


Figure A1. Transect locations for fish, mobile invert, and benthic surveys.

Table A1. Transect names, coordinates, and compass bearings

Zone	Transect	Latitude	Longitude	Compass bearing	Direction
Tidepool	T1	21.64943	-158.06363	10	N
Tidepool	T2	21.64985	-158.06349	70	E
Tidepool	T3	21.64996	-158.06303	310	NW
Tidepool	T4	21.65002	-158.06328	310	NW
Tidepool	T5	21.65048	-158.06340	320	NW
Tidepool	T6	21.65063	-158.06337	10	N
Tidepool	T7	21.65086	-158.06317	50	NE
Tidepool	T8	21.65057	-158.06265	285	W
Cove	C1	21.65122	-158.06268	135	SE
Cove	C2	21.65112	-158.06248	130	SE
Cove	C3	21.65119	-158.06245	35	NE
Cove	C4	21.65133	-158.06227	30	NE
Cove	C5	21.65160	-158.06213	290	W
Cove	C6	21.65170	-158.06236	300	NW
Cove	C7	21.65138	-158.06200	200	S
Cove	C8	21.65121	-158.06210	200	S

Fish and Mobile Invertebrate Surveys

Equipment

- GPS w/ dry bag (may not be necessary after locations are established)
- Transect reel
- Compass
- Waterproof watch with stopwatch function
- Data slate
- Data sheets
- Secchi disc
- Underwater camera

Notes

- Alternate weekly which area is surveyed in the morning vs afternoon
- Record human presence before and during each transect
- Aim for 5 minute survey time

Protocol

1. Navigate to transect start location
2. Fill out metadata: transect number, date, time etc.
3. Take a photo of your datasheet with metadata to help organize subsequent photos
4. Record and photograph human activities (number and type) in the vicinity of the transect (10 m radius from transect center)
5. Measure depth with the transect line and record with metadata
6. Fasten transect to substrate
7. Before swimming the transect line out, first observe the transect area and note any large or mobile fish that are likely to swim away once you start swimming and note these on your data sheet
8. Start timer for 5 minutes and slowly swim along the 10 x 4 m transect in the established direction (using compass if necessary,) reeling out line along the way, and identify and count all fishes visible within 2 m to either side of the centerline
    a. Care should be taken to make sure transect line is straight and taut
9. After reeling out the transect line, fasten it to the other side and swim back along the transect to finish out 5 minutes of surveying fish. The second pass back along the transect line should be mostly focused on identifying and counting more hidden, small, and cryptic species
    a. If possible without disrupting the count, snap photo/s of any fishes not able to be identified
10. Record number, activity, and duration of any humans occurring within the transect area during the 5 min survey period, take photos if convenient
11. Upon completion of the fish count, swim back along the transect and count all mobile invertebrates (sea cucumber, sea urchins, crabs, etc.) occurring within 2 m to either side of the centerline.
    a. Time spent should be ~ 5 min

b. Photograph any species not identifiable in the field to identify later

12. Once back at the start of the transect, place secchi disc at the transect start (prop it up or wedge it between rocks so it is upright and visible.) Swim along the transect until the black patches are not distinguishable from the white patches, reeling out additional line if necessary. Record the distance for visibility/turbidity.
13. Reel in the transect line and proceed to the next transect location.
14. Repeat for all 8 transects in an area, take a break for a snack/warming up, then repeat in the afternoon for 8 transects in the second area

Fish Survey Guidelines

A visual census aims to record an instantaneous estimate of abundance for the target species present within the bounds of the transect. Though it is physically impossible to census the entire transect in a given instance, it is possible to treat the transect as a series of instantaneous counts, such that each portion of the transect area is only surveyed once for target species.

- This is achieved by viewing ahead and counting fishes in an area of the transect well within the bounds of visibility. Increments of 5 m is a good guideline, however this may vary with water clarity. Transect marks or underwater features may be used to delineate transect sections
- During the first scan of the section the most mobile target species should be counted and recorded, with progressively less mobile species recorded in consecutive counts.
- Fish entering the transect during, or after, that area is sampled are not included as they were not present during the initial instantaneous count
- Once the most mobile species have been counted the observer moves along the center of the transect searching for more cryptic and slower moving species, being careful to include individuals of the most mobile species which were obscured from view by the structure of the reef during the initial count
- Observers should look forward periodically along the length of the transect to record highly mobile species entering the area, taking care not to re-count them during the more careful scan of that area
- For large mobile schools take a visual “snapshot” of the widest portion of the school and record only those individuals that are within the transect at that instance

Benthic Cover Quadrat Surveys

Equipment

- GPS w/ dry bag (may not be necessary after locations are established)
- 2 transect reels
- Compass
- 0.5 m PVC quadrat
- Small dive weight/s (1 lb)
- Weight belt
- Data slate
- Data sheets
- Underwater camera

Notes

- Alternate weekly which area is surveyed in the morning vs afternoon
- Record human presence before and during each transect

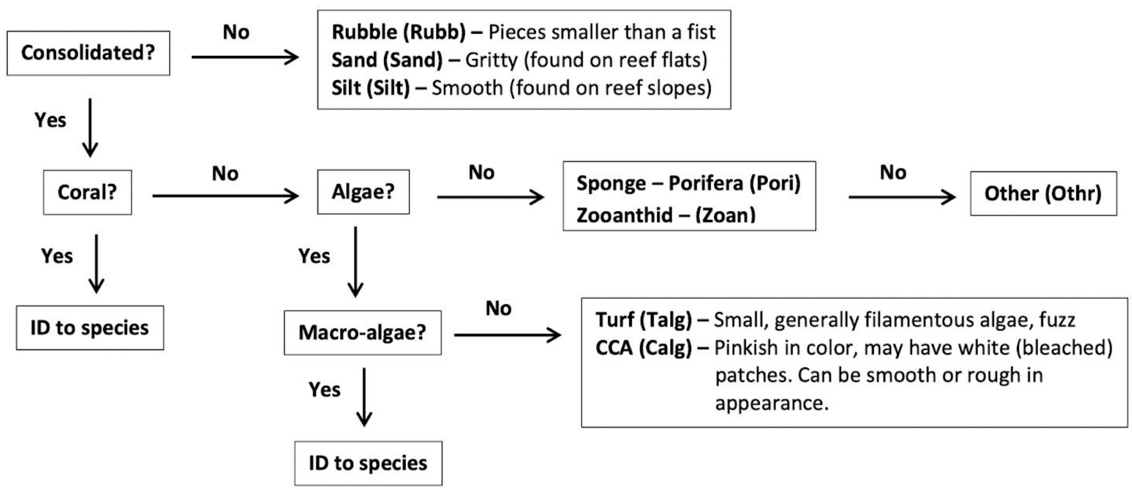
Protocol

1. Navigate to transect start location
2. Fill out metadata: transect number, date, time etc.
3. Take a photo of your datasheet with metadata to help organize subsequent photos
4. Measure depth with the transect line
5. Fasten transect to substrate
6. Reel out transect line and make the end of the transect line fast on the reef
7. Turn around and conduct rugosity measurement by draping or placing the additional transect tape along the centerline of the transect ensuring that the transect tape follows the contour of all natural fixed surfaces until reaching the start of the transect. Use 1 lb dive weights to hold down the transect incrementally if you need to swim up for air (rugosity measurements often require a short freedive at locations deeper than 1 m.) Note the resulting measurement for rugosity on the datasheet
8. Reel in rugosity transect
9. Proceed with benthic cover surveys by identifying substrate types on each of 16 intersections on a 0.5 m quadrat, for a total of 10 quadrats per transect on alternating sides of each 10 m transect line
    a. Place first quadrat along the right of the transect line so that the bottom edge of the quadrat aligns with the transect start
        i. Photograph the quadrat, making sure that the whole quadrat is visible at the steepest angle that water depth allows
        ii. Identify substrate occurring directly below each of the 16 intersections to the lowest possible taxa and note on the datasheet
        iii. If at all unsure about any algae identification, take photos to identify later
        iv. Record number, type and location (on transect), and take photo of damage to coral and algae within each quadrat and elsewhere on transect

   b. Place the second quadrat on the left side so that the bottom edge corresponds with the next meter mark and follow the same procedure
      i. *For transects 6 & 7, put all quadrats on left/west side of transects to focus on hard bottom/live-cover areas

10. When a total of 10 quadrats have been completed, roll in the transect line and navigate to the next transect location
11. *If notice any obvious human impact/damage off transect, make a note - species, type of impact - take photo and GPS point*

Benthic Cover Identification



Roving Coral Impact Survey

Equipment

- GPS unit in waterproof pouch attached to float with string/rope for towing
- Data slate
- Data sheets
- Measuring tape or stick (cm)
- Camera w/ UW housing

GPS Settings

GPS will automatically start tracking when turned on.

- Menu button (x2) > Setup > System > GPS Settings
  - WAAS/EGNOS > On
- Menu button (x2) > Setup > Tracks
  - Track log > Record, Show On Map
  - Record Method > Auto
  - Recording Interval > Normal

Notes

Use a GPS on a float in tracking mode (GPS must be on). Start at the south end of the tidepool and swim methodically back and forth (like a lawn mower) aiming to cover the entire tide pool and inner cove area up to 2m in depth.

Protocol

1. Starting from the south end of the tidepool (east of T1,) swim around attempting to visually cover all underwater areas in the tide pools and cove
2. Wherever a coral colony is observed that is greater than 10 cm and visible from the surface (living or dead,) record:
   a. Identification to species
   b. Take a photo and a waypoint and note ID numbers on data sheet
   c. Measure depth of coral at highest point and coral diameter along the longest axis in 5 cm size bins. Record both on datasheet
   d. Record if there is any visible damage and note type (break, scrape, or scrub - algae covered) and approximate size diameter (in cm along longest axis) of damaged area
   e. Record any other relevant observations
3. Continue on roving survey
4. Survey may be paused for breaks by taking and noting ending waypoint and end time and turning off GPS. When resuming, turn on GPS and start from the last waypoint noting new start time.

Appendix 2 – Tourist tracking protocol

Objective:
To support research on the biological carrying capacity of high-use areas of the Pūpūkea MLCD – the tidepools and inner cove – by collecting data on substrate impacts and spatial patterns of human use. Specifically, this additional study component aims to address the following questions:

- What are spatial patterns of human use as revealed through individual visitor activities?
- What is the frequency and nature of visitor substrate contact?

Subjects:
This activity will collect data on the following in-water activities taking place in the Pūpūkea MLCD originating in the tidepool or anywhere in the inner cove (primary entry points in Fig. 1).

- Snorkeling - Swimming with mask and snorkel (fins optional)
- Swimming - Swimming without a mask and snorkel
- Wading - Walking in shallow water (no mask and snorkel)
- SCUBA - Diving with SCUBA gear

In a given survey day, observers should aim to collect data on a variety of the above activity types.

Time-frame:
Surveys can take place any day of the week, between the hours of 9am and 5pm - when human use is highest. For safety reasons, surveys will be limited to a maximum of three two-hour sessions with 30 min breaks in-between. However, observers should aim to finish each survey (continue until the subject exits the water).

Equipment list:

- Snorkel gear: mask, snorkel, fins w/booties, wetsuit
- GPS unit in waterproof pouch attached to float with string/rope for towing
- Data sheet concealed on fish ID card (w/ rubber bands)
- 2 pencils (one for backup)

Protocol:
Observers equipped with snorkeling gear and a GPS unit will follow individuals for the full duration of their “dives'' - defined here as any of the in-water activities listed above - from point of entry to point of exit from the intertidal zone. Observers should aim to blend in with the crowd and remain undetected by their subject. Subsequent surveys should aim to record different types of activities.

Please be sure the GPS unit remains on top of the float and above the water in order to maintain satellite connectivity for tracking.

- Start at or near one of the three main entry points/beaches (Tidepool center, Cove S, Cove N) and select a subject getting ready to enter the water
- Turn on the GPS unit - which is already in tracking mode
- Note entry location on data sheet (see datasheet key below)
- Note type of activity on data sheet (see datasheet key below)
- Note the GPS time (to the minute) the subject enters the water - on Compass page of GPS, hit "Page" button until see compass and time of day
- Enter the water at the same location and discreetly follow the subject for the duration of their dive
- When and if they begin swimming, take a waypoint at that location
- Wherever there is a transition from swimming to walking and vise-versa, take a waypoint
- If there is contact with live substrate (coral, algae, inverts) while walking, take a waypoint and notes
- While the subject is swimming, watch for any substrate contact and take a waypoint and make notes at each contact location
    - This excludes steps taken to enter and exit the water (unless live substrate is involved), begin noting substrate contact after the snorkeler has started their dive (usually in a horizontal position). Note the following on the datasheet along with the waypoint number:
    - Waypoint (Garmin GPS 73)
        - Press "Mark" button
        - Note waypoint number (at top of screen) on datasheet
        - Press "Select" (*Done* selected on screen) button to store waypoint
    - Type of contact
        - Hand, foot, standing
    - Substrate type
        - Sand, uncolonized rock, coral (mound, branching, encrusting), CCA, sessile inverts, mobile inverts, turf, macro-algae
    - Result of contact
        - Visible damage?
        - Provide short description
- Note the GPS time (to the minute) when the subject exits the water.
- Exit at the same location and turn off the GPS when on land to end the survey track.

Data Entry:

- Take a photo (with your smartphone) of your datasheets as a backup in case it gets lost or damaged before you are able to enter the data
- Enter data within 24-48 hrs of your survey. This ensures it is fresh in your mind in case there are any missing details etc. on your datasheet.

Datasheet:

Surveyor: Pupukea MLCD Visitor tracking

Date	Start	End	Entry	Type & GPS #	Date	Start	End	Entry	Type & GPS #
Cont	Subs	Waypoints		Notes	Cont	Subs	Waypoints		Notes

Datasheets are designed for multiple surveys. First row of each survey will have survey metadata (date, times, etc.), subsequent rows will list substrate contact data.

Key (suggested codes in parenthesis):

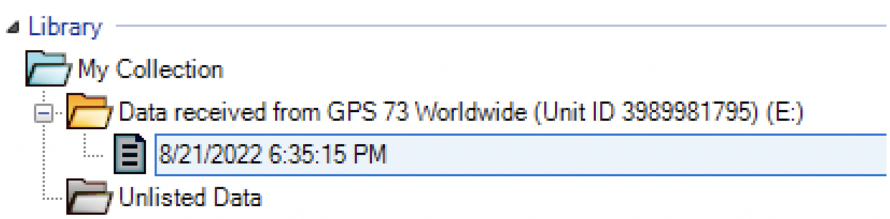
- Metadata
    - Date - Date surveys conducted
    - Start - Start time (24hr time) of survey: when subject enters the water
    - End - End time (24 hr time) of survey: when subject exits the water
    - Entry - Entry point: Tidepool center (T), Cove S (S), Cove N (N), Tidepool other (TO), Cove other (CO)
    - Type - Snorkeler (Snork), Swimmer (Swim), Wader (Wade), SCUBA
    - GPS # - GPS number written on the float
- Substrate contacts
    - Cont - Type of contact: hand, foot, standing (stand), other
    - Subs - Type of substrate: Sand, uncolonized rock (rock), mound coral (cor mo), branching coral (cor br), encrusting coral (cor en), Crustose coralline algae (CCA), sessile inverts - non-mobile inverts other than coral (inv ses), mobile inverts (inv mob), turf, macro-algae (algae)
    - Waypoints - List applicable waypoint/s here.
    - Notes - Specific to living substrates, note if/if not visible damage (vis/none) and short description. If two waypoints denote start and stop points for wading, note wading here.

GPS Settings

- Garmin GPS 73 Setup
    - Menu button (x2) > Setup > System > GPS Settings
        - WAAS/EGNOS > On
    - Menu button (x2) > Setup > Tracks
        - Track log > Record, Show On Map
        - Record Method > Auto
        - Recording Interval > Normal
    - Compass page (Page button until see large compass) > Menu button (x1) > Change Data Fields > Change to Time of Day
    - Compass page > Menu button (x1) > Change dashboard > Large Data Field

GPS download

- Download [Garmin BaseCamp] (free) program
- Connect GPS to computer using USB cable
    - You should see USB symbol on GPS screen and get a notification on your computer that the GPS device is connected
- Open Garmin BaseCamp program
    - You should see the GPS device listed in the "Library" (top left window)
- On the menu at the top of the screen select: Device > Receive from Device…
    - You will see a folder appear in the "Library" with the downloaded data



- Select the data file as shown above
- Then on the main menu select: File > Export
    - Create and navigate to a file on your computer to store the GPS data
    - Keep the default file name except add in the GPS number in front Example: "GPS1 8_21_2022 6_35_15 PM"
    - Save as type: Comma-delimited text (*.csv)
- Repeat the above steps, this time Save as type: GPS eXchange Format (*.gpx)
- Copy/Paste or Drag & Drop both files to Shared Google Drive folder: **Tourist Tracking > GPS data**